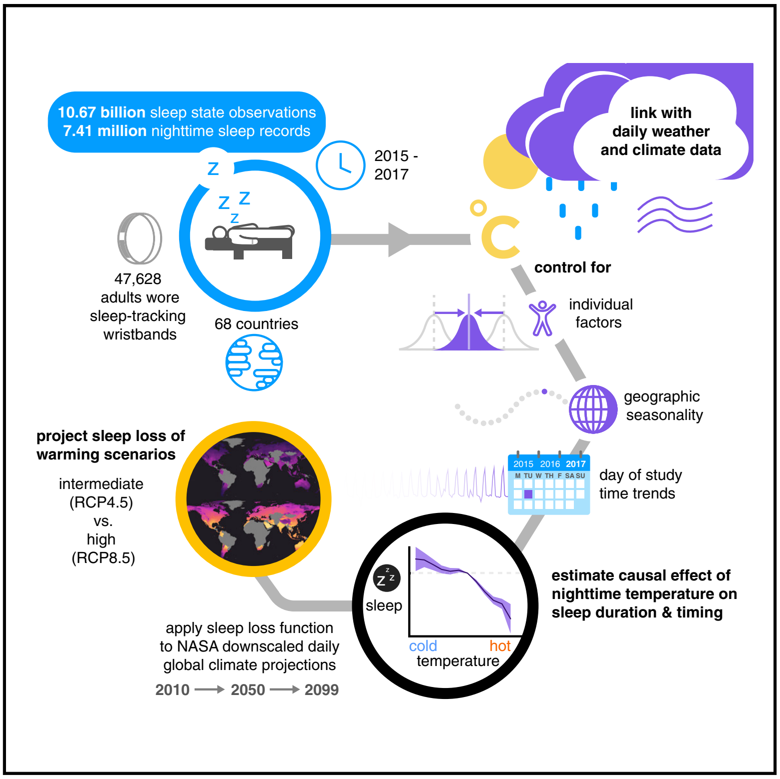
One Earth

Article

# Rising temperatures erode human sleep globally

## Graphical abstract



## Highlights

- Warmer temperatures reduce sleep globally, amplifying the risk of insufficient sleep
- The elderly, women, and residents of lower-income countries are impacted most
- Those living in warmer climates lose more sleep per degree of temperature rise
- Climate change is projected to unequally erode sleep, widening global inequalities

## Authors

Kelton Minor, Andreas Bjerre-Nielsen,
Sigga Svala Jonasdottir,
Sune Lehmann, Nick Obradovich

## Correspondence

kmi@samf.ku.dk (K.M.),
obradovich@mpib-berlin.mpg.de (N.O.)

## In brief

In a global-scale natural experiment featuring over 10 billion minute-level sleep observations from sleep-tracking wristbands, we found that increases in nighttime temperature harm human sleep across nearly the entire range of observed temperatures, with sleep loss and the risk of insufficient sleep increasing steeply when nights exceed 10°C. Our findings have significant implications for international, regional, and local climate adaptation planning and illuminate a pathway by which increasing heat may unequally impact human functioning, productivity, and health globally if unmitigated climate change continues.

Minor et al., 2022, One Earth *5*, 1–16
May 20, 2022 © 2022 Elsevier Inc.
https://doi.org/10.1016/j.oneear.2022.04.008

CellPress

One Earth

CellPress

Article

# Rising temperatures erode human sleep globally

Q1 Kelton Minor,[1,5,*] Andreas Bjerre-Nielsen,[1,2] Sigga Svala Jonasdottir,[3] Sune Lehmann,[1,3] and Nick Obradovich[4,*]
[1]Copenhagen Center for Social Data Science, University of Copenhagen, Copenhagen, Denmark
[2]Department of Economics, University of Copenhagen, Copenhagen, Denmark
[3]Department of Applied Mathematics and Computer Science, Technical University of Denmark, Kongens Lyngby, Denmark
[4]Center for Humans and Machines, Max Planck Institute for Human Development, Berlin, Germany
[5]Lead contact
*Correspondence: kmi@samf.ku.dk (K.M.), obradovich@mpib-berlin.mpg.de (N.O.)
https://doi.org/10.1016/j.oneear.2022.04.008

**SCIENCE FOR SOCIETY** Insufficient sleep is a risk factor for several adverse physical and mental outcomes. A lack of sleep has been associated with reduced cognitive performance, diminished productivity, compromised immune function, adverse cardiovascular outcomes, depression, anger, and suicidal behavior. Rising temperatures have been associated with reduced sleep, but little is known regarding the influence of rising outdoor temperatures and weather conditions and the effects of climate change. When compared with global weather measurements, sleep-tracking data from wristbands reveal that warmer nighttime temperatures do indeed harm sleep, with the effects unequal. The elderly, residents of lower-income countries, females, and those already living in hotter climates are disproportionately impacted. Further analysis reveals that climate change is already impairing human sleep, and should greenhouse gas concentrations not be stabilized until the end of the century, each person could be subjected to 2 weeks of short sleep each year.

## SUMMARY

Ambient temperatures are rising worldwide, with the greatest increases recorded at night. Concurrently, the prevalence of insufficient sleep is rising in many populations. Yet it remains unclear whether warmer-than-average temperatures causally impact objective measures of sleep globally. Here, we link billions of repeated sleep measurements from sleep-tracking wristbands comprising over 7 million sleep records (n = 47,628) across 68 countries to local daily meteorological data. Controlling for individual, seasonal, and time-varying confounds, increased temperature shortens sleep primarily through delayed onset, increasing the probability of insufficient sleep. The temperature effect on sleep loss is substantially larger for residents from lower-income countries and older adults, and females are affected more than males. Those in hotter regions experience comparably more sleep loss per degree of warming, suggesting limited adaptation. By 2099, suboptimal temperatures may erode 50–58 h of sleep per person-year, with climate change producing Q2 geographic inequalities that scale with future emissions.

## Q3 Q4 Q5 Q7 Q6 INTRODUCTION

Converging evidence suggests that climate change is challenging human mental health and cognitive functioning, although the behavioral mechanisms remain unclear.[1–10] Recent research based on self-reported data—limited to the United States—suggests that sleep may constitute one such pathway.[11–13] Regular and sufficient sleep supports human physical and mental health.[14] Short sleep duration is associated with reduced cognitive performance,[15,16] diminished productivity,[17] increased absenteeism,[18] compromised immune function,[19] and elevated risk of hypertension, adverse cardiovascular outcomes,[20,21] mortality,[20,22] depression, anger, and suicidal behaviors.[23,24] Acute sleep restriction delays reaction times,[15] increases accident risk,[25] inhibits the neural encoding of new experiences to memory,[26] and limits the clearance of neurotoxic metabolites from the brain linked to aging and neurodegenerative diseases.[27] Nevertheless, growing proportions of industrialized populations do not obtain adequate sleep, a development attributed to lifestyle and environmental changes, but not yet fully understood.[17,28,29] Concurrently, nighttime ambient temperatures are increasing due to both anthropogenic climate change and the expansion of urban heat islands.[30,31] To inform policy, planning, and practice, more information is needed about the environmental factors that curtail or promote sufficient sleep globally, particularly the role played by outdoor ambient temperature.[12,32]

Prior research investigating the influence of ambient temperature on sleep in adults has been largely restricted to short controlled laboratory studies or imprecise self-report surveys. Humans and other mammals have developed both neurophysiological and behavioral processes to coordinate rhythms of thermoregulation and sleep, presumably to conserve energy expenditure.[33] In humans, the maximal rate of core body cooling is strongly correlated with sleep onset, and sleep propensity peaks near the minimum of the core body temperature rhythm.[34,35] Preceding sleep onset, increased blood flow to the distal skin and extremities enables cooling of the core body temperature.[36] Both skin and core body temperatures become more sensitive to environmental temperature during sleep, and duration of wakefulness has been shown to increase when temperatures warm or cool outside of the thermoneutral zone—the range of ambient temperatures where the body can maintain its core temperature only through regulating dry heat loss (skin blood flow)—albeit under controlled conditions that constrain human adaptation.[37]

Far less is known about the influence of outdoor ambient temperatures and meteorological conditions on adult sleep in real-world settings.[12] Evidence from self-report studies indicates that the prevalence of reported sleep deficiencies increases in warm weather.[11,13,38,39] The largest of these studies pooled data in the United States from nationally representative health surveys and found that higher monthly nighttime temperature anomalies increased self-reported nights of insufficient sleep during the previous month. However, retrospective self-reported sleep outcomes are notoriously imprecise, unreliable, and have been shown to have questionable internal validity.[40,41] Thus, it remains an open question whether, and to what extent, ambient thermal and weather conditions might affect objective repeated measures of individual sleep duration and timing across a global adult population.

In contrast to the limited precision and resolution of the subjective and indirect measures employed by previous studies—even the largest of which only used data from one country—the global reach of sleep-tracking wristbands holds promise for understanding the environmental determinants of human sleep. Here, we draw on a large-scale sleep dataset of over 10 billion sleep observations registered from 2015 to 2017, comprising 7.41 million repeated daily sleep records spanning 68 countries using accelerometry-based sleep-tracking wristbands linked to a smartphone application (Figures 1B and 1D). This sleep dataset replicates established age, interregional, and socio-temporal sleep characteristics (Experimental procedures; Tables S1 and S2; Figure 1C). Accelerometry-based sleep tracking devices are increasingly ubiquitous and particularly well suited for large-scale observational studies,[42] offering several empirical advantages over previous research designs. *In situ* sleep measures from sleep-tracking wristbands provide dynamic spatial and temporal reference information for precise merging with meteorological data across diverse geographic regions, enabling the study of the effect of temperature on within-individual changes across the entire sleep period. Moreover, objective measures of total sleep duration can be used to investigate whether temperature affects the probability of obtaining short sleep, following standard definitions.[14]

To investigate whether ambient temperature alters sleep, we pair our sleep observations of nighttime sleep duration (total sleep time) and timing (sleep onset, midsleep, and offset) with geolocated meteorological and climate data (Figures 1A and 1B; Experimental procedures). We specify multivariate fixed-effects panel models[43]—derived from the climate econometrics literature[44,45]—with individual repeated measures, using as good as random variation in meteorological variables relative to local averages to estimate the total effect of ambient nighttime temperature on individual sleep outcomes (Tables S6 and S7). An advance of the present study is that our dataset allows us to control for all stable individual characteristics and leverage within-person fluctuations in both weather exposures and sleep outcomes to isolate the plausibly causal effect of nighttime temperature on our person-level sleep outcomes while controlling for other potentially confounding individual-level, calendar-date-specific, and subnational administrative region-by-month spatiotemporal factors that might otherwise bias inference between temperature exposures and sleep outcomes. Importantly, this statistical model also controls for location-by-date historical climate normals and cloud-cover alterations in daylight, removing the potential confounding effect of seasonality from our analyses (Tables S6–S8 and S30). Thus, whereas sleep laboratory research in this setting typically manipulates ambient room temperatures while limiting behavioral adaptation, the present study seeks to instead estimate the total effect of quasi-random changes in outside ambient temperatures on sleep patterns, allowing for habitual behavioral adjustments to temperature, including possible responses to the environmental information conveyed by outdoor conditions. This latter point is important for studying temperature-sleep relationships under ecologically valid circumstances, because even awareness of outdoor ambient conditions while indoors may impact sleep behavior at night.

Summarizing our empirical results, we find that adults fall asleep later, rise earlier, and sleep less during hot nights. Deviating from the results of laboratory studies that constrained adaptive behavior, we show that increases in nighttime temperature reduce time slept across the global temperature distribution, with effects increasing in magnitude as temperatures become hotter. The effect of a 1°C increase in minimum temperature among the elderly is over twice the effect observed in other age groups. Further, the effect is nearly three times as large among globally poorer individuals as it is among individuals in richer nations and is significantly larger in females as compared with males. We do not find evidence of sleep adaptation to warmer temperatures within days, between days, across summer months, or between climate regions. Indeed, the sleep impact per degree of temperature increase in warmer locations is significantly larger than in colder locations. Our results imply that suboptimal ambient temperatures likely already erode human sleep considerably early in the 21st century. Coupling our model estimates with downscaled climate model output, we project that climate change may exacerbate global environmental inequalities by disproportionately eroding sleep in the warmest regions, with differential societal sleep impacts scaling with future atmospheric greenhouse gas concentrations. We verify that our primary conclusions are robust to alternative sample inclusion criteria, meteorological data, temporal controls, and outcome measures (Tables S6–S20, S30, S31, S49, and S50; Figures S2 and S3). Further, our modeling framework

Please cite this article in press as: Minor et al., Rising temperatures erode human sleep globally, One Earth (2022), https://doi.org/10.1016/j.oneear.2022.04.008

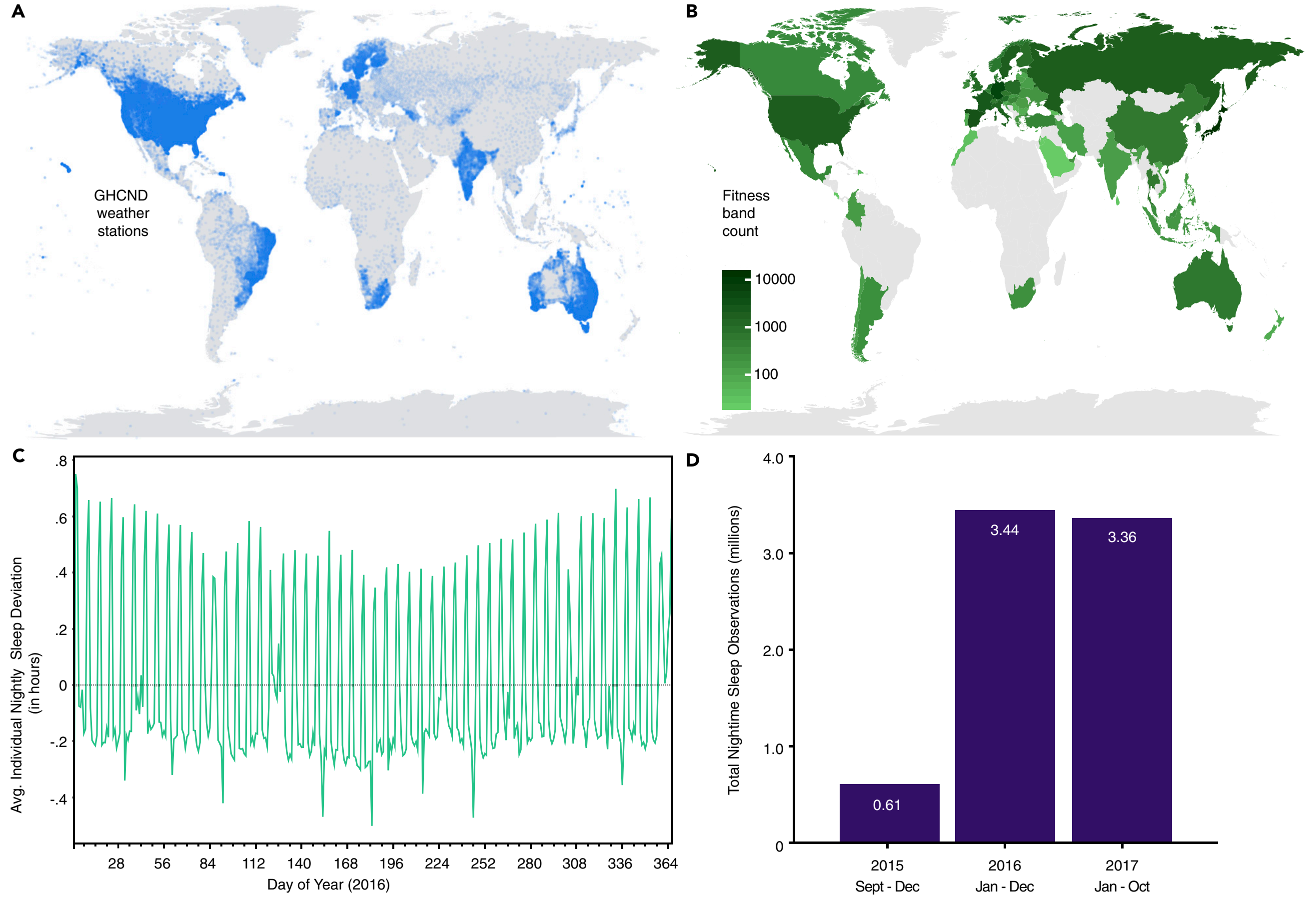


**Figure 1. Global weather station and sleep data coverage**

(A) Plotted map of weather stations from the Global Historical Climatology Network-Daily (GHCND). Each blue dot represents one station.

(B) World map depicting the country-level count of accelerometry-based sleep-tracking wristband users included in this study, spanning 68 countries from all continents except for Antarctica. Countries with relatively more users appear as darker shades of green.

(C) Plot showing regular and dynamic temporal patterns in within-individual sleep duration deviation from average (in hours) over the 2016 calendar year. Each daily measure corresponds to the mean of all within-individual nightly sleep deviations for active users on that day. Recurring weekend peaks (above zero) and weekday valleys (below zero) reflect the imbalanced temporal structure of the adult working week—whereby sleep reduction during weekdays is partially compensated for on weekends with oversleep.

(D) Annual total number of nighttime sleep observations collected over the 2-year period from September 2015 through October 2017, in millions.

controls for any unobserved, fixed device characteristics, and we confirm that the period and frequency of sleep-tracking wristband use does not alter our primary results (Experimental procedures; Tables S32 and S33).

## RESULTS

### Effects on sleep duration and short sleep probability

The results of our binned temperature regressions indicate that exogenous increases in nighttime ambient temperature reduce adult sleep duration across nearly the entire observed temperature distribution (Figures 2A and S2). Climate change is projected to continue to increase the magnitude and frequency of extreme nighttime temperatures beyond the recent historical record. Our data indicate that, on very warm nights (>30°C), sleep declines by 14.08 min (−10.61 to −17.55) compared with nights with the lowest temperature-attributed sleep loss in our sample. Increasing nighttime temperatures amplify the estimated probability of obtaining a short night of sleep, measured with multiple standard definitions for insufficient sleep.[14] The probability of sleeping less than 7 h increases gradually up to 10°C, before increasing at an elevated rate. Nighttime minimum temperatures greater than 25°C increase the probability of getting less than 7 h of sleep by 3.5 percentage points compared with the temperature baseline of 5°C–10°C (Figure 2D). However, our results show that the optimum nighttime ambient temperature for sufficient sleep may be considerably lower than this baseline, with nighttime heat inducing short sleep across most of the temperature distribution. Providing scale for this estimated relationship, exposure to nighttime temperatures exceeding 25°C, if extrapolated for an equivalent population of 100,000 adults across a single night, would result in 4,600 additional individuals obtaining a short <7-h night of sleep compared with the estimated optimum minimum nighttime temperature.

Please cite this article in press as: Minor et al., Rising temperatures erode human sleep globally, One Earth (2022), https://doi.org/10.1016/j.oneear.2022.04.008

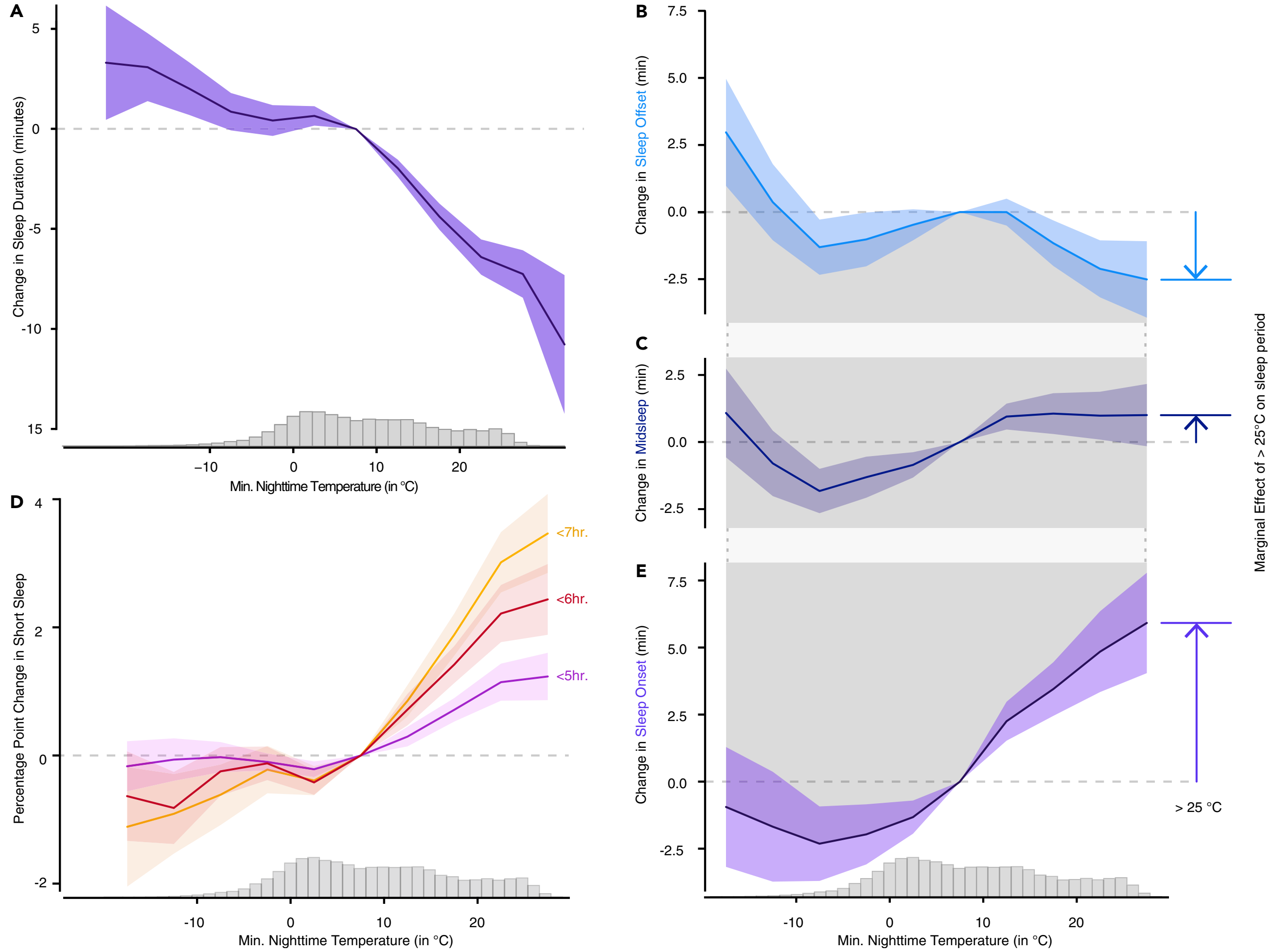


**Figure 2. Increasing temperature shortens the human sleep period**

(A) Plot of the relationship between increases in nighttime minimum temperature and the average within-individual change in sleep duration for each temperature bin. As minimum temperatures rise, sleep duration decreases with a steeper linear decline when temperatures exceed 10°C. Shaded regions represent 95% confidence intervals computed using heteroskedasticity-robust standard errors clustered on the first administrative division level. Histograms plot the distribution of observed nighttime temperatures across millions of sleep observations. We confirm sufficient observational support across all temperature bins (Table S5).

(B) High nighttime temperatures significantly compress the human sleep period, primarily through a delay in sleep onset and a marginally smaller advance in sleep offset. Sleep offset advances under higher nighttime temperatures >15°C, while very cold temperatures below −10°C delay offset timing.

(C) Nighttime temperature increases above −10°C marginally delay midsleep—the midpoint of the human sleep period—although the magnitude of change at higher temperatures is smaller than concomitant changes in sleep onset and offset.

(D) A plot of the predicted change in the probability of obtaining a short night of sleep across each minimum temperature bin. As temperature increases above 5°C, the probability of obtaining a short night of sleep—measured with three standard criteria—also increases.

(E) Above −10°C, increasing nighttime ambient temperatures delay sleep onset across the observed temperature distribution.

Our results are robust, even when employing more extreme thresholds of short sleep, including <6 h and <5 h, demonstrating that marginal losses in total sleep time with rising temperatures predisposes people to insufficient sleep attainment (Figure 2D; Tables S9 and S10). Further, since prior evidence from aggregated mobile phone calling data suggests that people may compensate for seasonal sleep reductions during the summer with afternoon naps, we check that our primary results are robust to replacing nighttime sleep duration with 24-h sleep duration.[46] Contrary to the hypothesis that total sleep time might be conserved, we find that including daytime sleep actually slightly increases the effect size of temperature on within-individual sleep loss within our sample (Tables S8 and S29). Moreover, constraining our sample to only include high-income countries does not alter our primary results (Tables S49 and S50).

Our finding that human sleep is unidirectionally sensitive to increasing ambient temperatures across the temperature distribution differs from previous experimental studies that found reductions in sleep under both high and low environmental temperatures.[37] Instead, our within-person global analysis uncovers a similar functional relationship as those identified by prior national survey analyses using subjective measures of sleep.[11,13] In real-world settings, humans appear to be better at adapting their surroundings to obtain sufficient sleep under cooler outside conditions, whereas sleep loss increases with rising ambient temperatures. Since other meteorological factors may also influence sleep, we use our primary flexible model specification (Experimental procedures; Equation 1) to estimate the human sleep response to changes in weather. Sleep loss increases further as a function of the diurnal temperature range—the difference between daily maximum and minimum temperature. This result is directionally consistent with the diurnal temperature range attributed mortality response identified by a recent multi-country analysis.[47] Since our specified model controls for other weather variables, including cloud cover and relative humidity, two plausible explanations are that indoor environments may retain heat gained during the day or that daytime heat may impart physiological demands that extend into the sleep period. Importantly, diurnal temperature range is projected to increase annually over Europe[48] and separately across most other regions during summer months under a high-emissions, climate-change scenario.[47] By contrast, high levels of precipitation, wind speed, and cloud cover each marginally increase sleep duration (Figure S1). Compared with moderate levels of relative humidity, both low and high levels reduce sleep, with the former producing greater sleep reduction, providing initial evidence that dry conditions may curtail sleep.

Q8

### Effect on sleep onset, midsleep, and offset

To investigate how the entire sleep period responds to temperature-driven sleep loss, we construct separate flexible models to predict sleep onset, midsleep, and offset timing. Drawing on these combined estimates, we show that rising temperatures compress the human sleep period through both a larger delay in sleep onset and a moderate advance in sleep offset. As minimum temperatures rise above −10°C, delays in sleep onset curtail sleep duration (Figures 2A–2C and 2E) and marginally delay midsleep. By contrast, nighttime temperature increases advance sleep offset timing when temperatures exceed 15°C. Thus, larger declines in sleep duration at warmer nighttime temperatures are jointly driven by both delays in sleep onset and advances in sleep offset, constricting the human sleep period and slightly delaying midsleep (Tables S12–S14).

### Temperature effects by age group

Individual and environmental demographic factors may modify the impact of temperature on sleep. Older adulthood is marked by an attenuated thermoregulatory response to suboptimal environmental temperatures, earlier sleep timing, and reduced total sleep duration.[49] Such age-related developments may increase the nocturnal sensitivity of the elderly to higher ambient temperatures, possibly challenging sleep demand. We find that older adults (>65) are markedly more sensitive to exogenous increases in nighttime ambient temperature than mid-aged adults and young adults (Figure 3A). The per-degree effect of nighttime temperature on lost sleep for older adults (coefficient: −0.61) is over two times ($p < 0.01$) the effect estimated for mid-age adults (coefficient: −0.28). These results add to increasing evidence of the age-related ambient temperature sensitivity of sleep.[11,50] To explore the emergence of heightened temperature sensitivity in later life, we run an alternative specification featuring smaller age groups for every 10-year increment above 30 years of age. We show that heightened temperature sensitivity may emerge rapidly after age 60 and increase further beyond age 70 (Table S23).

### Temperature effects by sex

Under identical conditions, females' core body temperatures decrease earlier in the evening compared with males,[51] possibly exposing females to higher environmental temperatures around their time of habitual sleep onset. Females have also been shown to have greater subcutaneous fat thickness, which might impair nocturnal heat loss.[38] Comparing the effect of minimum temperature on sleep duration between sexes reveals that the per-degree negative impact of nighttime temperature rise is significantly ($p < 0.01$) but only slightly larger for females (coefficient: −0.34) than males (coefficient: −0.27) in our dataset (Figure 3B). This finding adds to evidence that females may be more predisposed to adverse heat effects on health than males.[52,53]

### Temperature effects by country income level

Since access to infrastructure, cooling technologies, and other unobserved environmental resources may plausibly modify the extent to which temperature impacts sleep, we further test whether our results differ across country-income levels. We find that the effect of minimum nighttime temperature on human sleep loss is substantially larger for people residing within lower-middle-income countries (coefficient: −0.85) compared with countries with higher income levels (Figure 3C; Tables S25 and S26). The negative effect of nighttime temperature on sleep duration is 2.8 times greater ($p = 0.087$) for residents in lower-middle-income countries compared with those from high-income countries (coefficient: −0.30) and 3.6 times greater ($p = 0.057$) compared with upper-middle-income countries (coefficient: −0.23). Collectively, these results provide initial evidence that countries from all observed income levels are sensitive to the effect of ambient nighttime temperature on sleep, but the amount of sleep loss per degree increase may be disproportionately larger for people in lower-middle-income countries.

### Temperature effects by season

To determine whether increases in minimum temperatures impact human sleep differently over the course of the year, we inspect the marginal effect of temperature on sleep loss across each season, accounting for hemispheric differences in seasonality. Nighttime temperature increases result in sleep loss throughout the year (Figure 3D). Consistent with the annual temperature distribution, we find that rising nighttime temperatures decrease sleep duration the most during summer months (coefficient: −0.55), followed by fall (coefficient: −0.35), spring (coefficient: −0.25), and winter (coefficient: −0.20) months (all coefficients are significantly different from zero at the $p < 0.01$ level). The per-degree effect of an increase in nighttime temperature on sleep loss during the summer is nearly three times larger than in the winter. Our results provide further evidence that temperature increases impart the largest losses on human sleep when nighttime temperatures are already elevated (Figure 2A; Table S21).

### Effects by average annual nighttime temperature decile

Those who reside in warmer areas with generally higher temperatures may respond to temperature increases differently than

Please cite this article in press as: Minor et al., Rising temperatures erode human sleep globally, One Earth (2022), https://doi.org/10.1016/j.oneear.2022.04.008

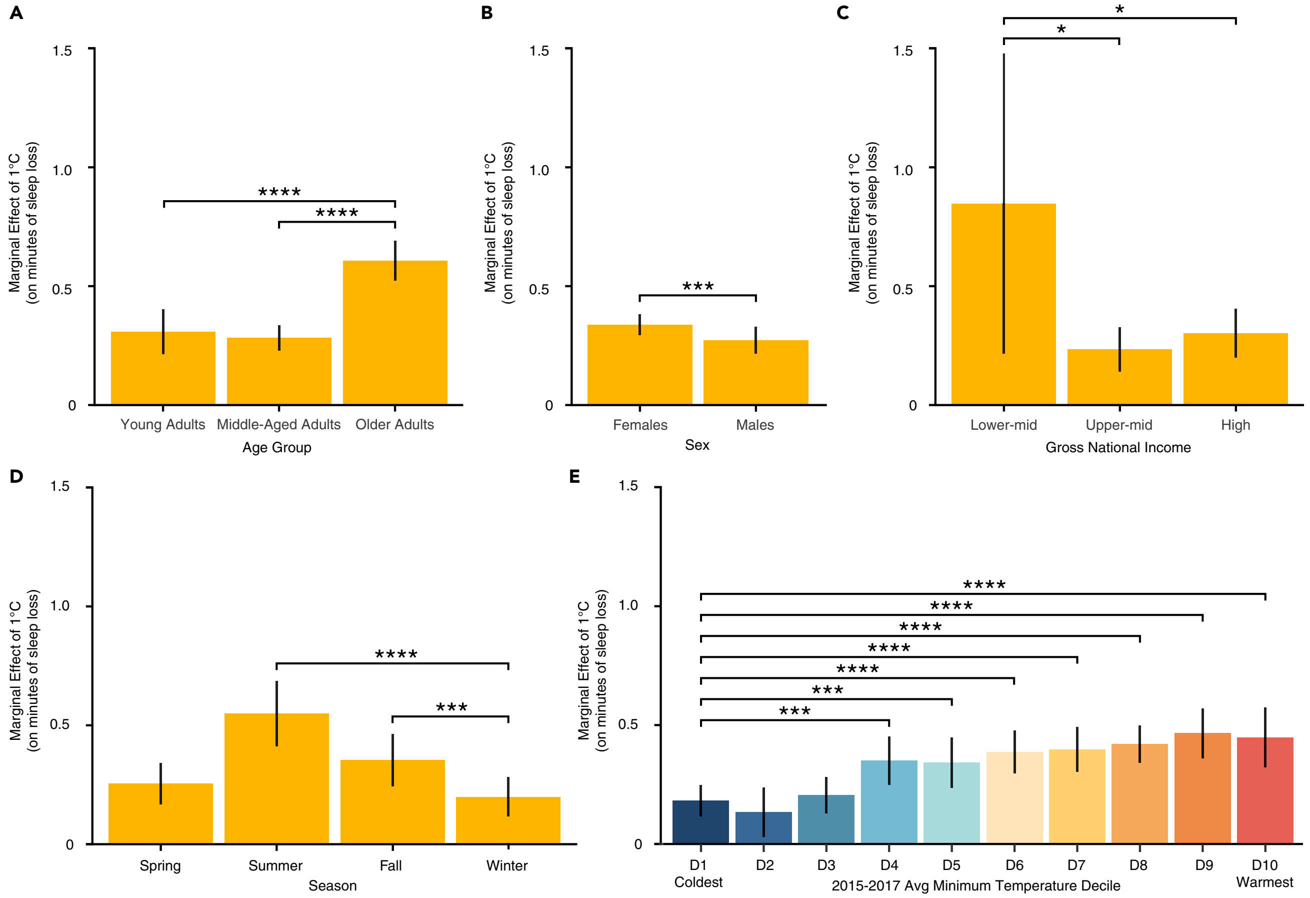


**Figure 3. Demographic, seasonal, and regional subgroup analyses**

(A) The marginal effect of temperature by age category on sleep loss produced by interacting age group with nighttime minimum temperature within our primary model specification (Experimental procedures; Equation 2). The marginal effect of increasing temperature by 1°C on sleep loss is nearly twice the magnitude for older adults (n = 1,289 adults; n = 155,922 observations) compared with mid-aged adults (n = 39,460 adults; n = 4,078,623 observations) and young adults (n = 2,364 adults; n = 170,626 observations).

(B) The marginal effects of temperature by sex on sleep loss. Those who identify as female (n = 13,302 adults; n = 1,279,271 observations) lose more sleep per degree increase in minimum temperature compared with those who identify as male (n = 29,811 adults; n = 3,125,900 observations).

(C) Plot of the marginal effects of nighttime minimum temperature by country-level gross national income (GNI). The effect of temperature on sleep loss is substantially larger for people residing within lower-middle-income countries (n = 995 adults; n = 14,639 observations) compared with upper-middle- (n = 5,910 adults; n = 274,488 observations) and high-income countries (n = 38,675 adults; n = 4,116,044 observations).

(D) The marginal effects of nighttime minimum temperature by season of the year on sleep loss. Temperature increases are associated with the greatest sleep losses during summer nights, followed by fall, spring, and winter nights.

(E) Marginal effects of a 1°C increase by average minimum temperature decile over the 2015–2017 period, from coldest (dark blue) to warmest (red) locations. Temperature increases exert larger impacts in warmer regions compared with colder regions. Error bars represent 95% confidence intervals. ****$p < 0.001$, ***$p < 0.01$, **$p < 0.05$, and *$p < 0.1$.

those living in colder regions.[54] To investigate whether the effect of temperature differs by ambient climate context, we conducted a heterogeneity analysis by decile of average local minimum temperature over the 2015–2017 period (Experimental procedures; Table S28; Figure 3E). We find that, compared with the coldest average temperature decile, marginal effects of minimum temperature on sleep loss are significantly larger for residents of warmer deciles (4th–10th deciles). Those living in hotter regions experience comparably more sleep loss per degree of warming, suggestive of limited adaptation in warmer climates. These results appear consistent with our binned temperature specifications (Figure 2A), showing that temperature increases at colder temperatures yield smaller effect sizes.

## Intra-annual and inter-day adaptation

Since prior research suggests that people may be able to physiologically or behaviorally acclimatize to warmer temperatures over relatively short periods of time,[55] we further assess possible intra-annual and inter-day sleep adaptation to ambient temperature. First, we test whether human sleep responds differently to nighttime temperature increases experienced during the first month of summer—when nights with locally hotter temperatures are relatively newer—versus the last month of summer when they are more familiar.[55] While short-run acclimatization would be apparent if the effect of temperature on sleep duration diminishes from the first to the last month of summer, we instead find evidence that nighttime temperatures appear to incur similar to

Please cite this article in press as: Minor et al., Rising temperatures erode human sleep globally, One Earth (2022), https://doi.org/10.1016/j.oneear.2022.04.008

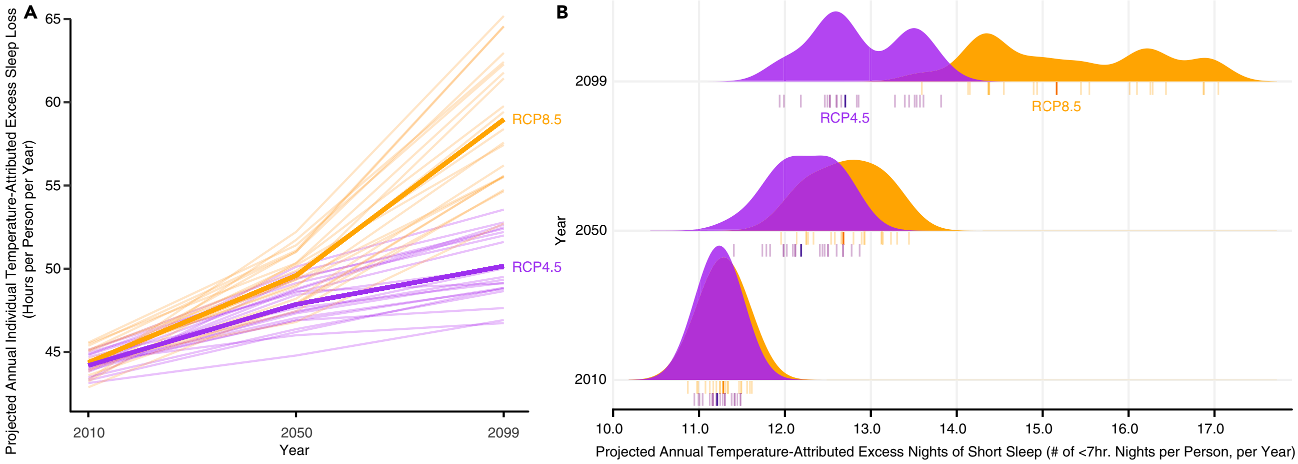


**Figure 4. Projected excess sleep loss by climate-change scenario**

(A) Global population-weighted average individual-level projections for the impact of elevated nighttime temperatures on hours of sleep loss under a midcentury stabilized atmospheric GHG concentration scenario (RCP4.5 in purple) and an increasing GHG concentration climate-change scenario (RCP8.5 in orange). Each line represents the estimated annual total per-person excess sleep loss due to suboptimal ambient temperature for a different downscaled climate model projection, averaged across all country-level pixels within the dataset. The dark colored lines plot the scenario-specific ensemble mean projected loss across 21 statistically downscaled global CMIP5 climate models. Sleep loss increases over time due to projected warming across all countries.

(B) Mean individual projections of the cumulative annual count of short (<7 h) sleep nights per person due to nighttime ambient temperature in 2010, 2050, and 2099. Rain cloud plots depict the distributions of projected annual sleep impacts across 21 bias-corrected and statistically downscaled CMIP5 climate models under RCP4.5 (purple) and RCP8.5 (orange) warming scenarios. Vertical marks beneath each distribution depict CMIP5 climate-model-specific projection estimates, with the median model projections shown as darkened marks.

marginally more sleep loss near the end of summer, when warmer temperatures are relatively less novel (Experimental procedures; Table S38). Second, after a given temperature exposure, people may physiologically adapt or otherwise shift when they get sleep via intertemporal substitution across days. For instance, short-term reductions in sleep due to temperature may in turn increase homeostatic sleep pressure that facilitates subsequent recovery of initial sleep loss.[56] Alternatively, previous days' thermal conditions may further disrupt sleep via delayed impacts not captured by our contemporaneous effect estimates. To account for this, we estimate a distributed lag model that includes lagged minimum temperature terms from the previous 7 days. We find that an increase in nighttime temperature produces additional delayed sleep loss: the sum of the contemporaneous and lagged coefficients is ~30% larger than the contemporaneous effect of temperature alone (Table S39). Coefficients remain negative through the 5th lag, with cumulative sleep loss growing up until a small partial rebound on days 6 and 7. These results persist when including lags for all weather variables or including temperature lags for each of the preceding 14 days (Tables S39 and S40), indicating that a rise in ambient temperature yields cumulatively larger net sleep loss rather than delayed sleep substitution.

## Annual individual sleep loss and short sleep projections

Finally, abiding by the assumption that future sleep loss will respond to projected changes in nighttime minimum temperature as they have responded to them in the recent past, we construct projections for the impact of ambient warming on cumulative annual individual sleep loss and temperature-attributed short sleep for all countries within our dataset (Figure 1B). Consistent with the climate impacts literature, we draw upon gridded data from 21 global climate models run under both end-of-century stabilization (Representative Concentration Pathway 4.5 [RCP4.5]) and increasing (RCP8.5) atmospheric greenhouse gas concentration scenarios and link downscaled, nighttime temperature projections with our spline regression model to compute the per-person average annual excess sleep loss expected at the beginning, middle, and end of the century (Figures 4A and 4B; Experimental procedures). Taking a world-population-weighted average across all grid-cell-level daily time series and each of the 21 climate models, we estimate that annual individual excess sleep loss due to suboptimal nighttime temperature was likely considerable near the beginning of the 21st century, with temperatures eroding an estimated 44 excess hours of sleep per person annually on average (Figure 4A) and contributing approximately 11 additional nights of short sleep per person annually, based on downscaled climate simulation data for 2010 (Figure 4B). Total annual sleep loss due to warming nighttime temperatures may steadily increase by midcentury, with yearly losses becoming markedly larger by 2099 under an increasing greenhouse gas (GHG) scenario but only moderately larger under a scenario in which atmospheric GHG concentrations stabilize by the end of the century (Figure 4A). Mean projected temperature-attributed individual excess sleep loss in 2099 varies from ~50 (range: 46.7–53.6) h per year in a stabilized GHG concentration scenario (RCP4.5) to ~58 (range: 52.7–65.2) h in an increasing GHG concentration scenario (RCP8.5). Sleep erosion is projected to exact growing societal sleep impacts, with the number of temperature-attributed short nights of sleep estimated to increase from ~11 per person per year in 2010 to ~12 short nights per year by 2050 under an intermediate RCP4.5 scenario. By the end of the century, nighttime temperatures may contribute to ~13 (range: 11.9–13.8) short

Please cite this article in press as: Minor et al., Rising temperatures erode human sleep globally, One Earth (2022), https://doi.org/10.1016/j.oneear.2022.04.008

nights of sleep per person per year under the stabilized RCP4.5 pathway and over ~15 (range: 13.6–17.0) short nights of sleep per year under the increasing GHG concentration (RCP8.5) pathway.

These globally averaged, population-weighted estimates mask considerable spatial heterogeneity in impacts, with projected geographic inequalities in temperature-driven sleep loss (Figures 5A–5D) expected to increase over time. Without further adaptation by the end of the century, residents in the warmest areas are projected to experience over 23 h of additional temperature-driven sleep loss per year by 2099 under a high GHG concentration scenario and 8.5 h of additional sleep loss under an intermediate stabilization scenario (Figures 5A–5D and S6), net of existing temperature-attributed excess sleep loss apparent in 2010 (Figure 4; Experimental procedures). Similarly, future warming is projected to unequally increase temperature-driven short sleep. Disparities in estimated net sleep erosion increase both over time and across space between warmer and colder regions under all scenarios (Figures 5E–5H), but differential impacts are projected to be more modest under an increasingly plausible scenario in which atmospheric GHG concentrations stabilize by the end of the century (RCP4.5). By the end of the 21st century, adults in the warmest regions are expected to experience approximately 3 additional nights of short sleep per year due to rising nighttime temperatures under the more moderate (RCP 4.5) scenario compared with upwards of 7 additional nights of short sleep under a "no policy" increasing GHG concentration (RCP 8.5) scenario. Critically, these projected changes are net of estimated temperature-attributed sleep impacts at the beginning of the 21st century (Figure 4), and our results indicate that suboptimal, warmer ambient temperatures likely already contribute to insufficient sleep globally (Figure 2D). Importantly, our historical estimates underlying these projections may also be conservative, since the majority of data arise from high-income countries and are skewed toward a middle-aged, male demographic (Experimental procedures). Indeed, our subgroup analyses indicate that future sleep loss may be larger by a factor of ~3 for lower-income countries, a factor of ~2 for demographically older populations and marginally higher for women (Figure 3). Moreover, the cumulative impact of lagged temperature effects likely exceeds the contemporaneous estimates used in these projections (Results; Tables S39–S41). Future planetary-scale research is needed that systematically investigates the impact of rising temperatures and other climate hazards on the sleep outcomes of vulnerable populations, particularly those residing in low-income countries and communities.

## DISCUSSION

In summary, we provide extensive evidence that human sleep is sensitive to nighttime ambient temperature, posing an additional climate-change-related threat to global public health and human well being. Increases in nighttime minimum temperature reduce sleep duration and increase the probability of obtaining insufficient sleep via the constriction of the human sleep period, primarily by delaying when people fall asleep. The effect of nighttime temperature on sleep loss is amplified for lower-income countries, older adults, and females. Our results suggest that temperature-driven sleep loss is evident across demographics, and increasing temperatures lead to some within-person sleep loss across all seasons, with the largest losses during the warmest months and on nights when minimum temperatures exceed 10°C. We do not find evidence of short-term acclimatization of sleep to warmer temperatures via intra-day, inter-day, or intra-annual substitution, and the marginal effect of increasing temperature is even larger for those already living in globally warmer regions compared with those residing in colder areas. Taken together, we find limited evidence of human sleep adaptation to hotter temperatures. We estimate that suboptimal nighttime temperatures likely already inflict considerable individual sleep loss early in the 21st century, and thus, increasing nighttime temperatures may further erode human sleep into the future. The burden of future warming will not be evenly distributed, barring further adaptation and mitigation, with people living in hotter climates expected to lose considerably more hours of sleep per year by 2099, contributing to societal impacts that scale with the level of future atmospheric GHG concentrations. Taken together, our results demonstrate that temperature-driven sleep loss likely has and may continue to exacerbate global environmental inequalities.

Our results carry significant implications for adaptation planning, policy, and research. Growing evidence faults increases in temperature with societal impacts to public health, behavior, and mental well being, although the causal mechanisms have remained poorly characterized.[1,4,7,9,10,45,57–64] Insufficient sleep increases the risk of many of the same negative physiological, behavioral, social, and economic outcomes shown to increase with high temperatures.[5–8,13,53,65–73] Thus, sleep may act as a key biobehavioral mechanism between ambient temperature and adverse human outcomes, with implications for human performance and productivity as well as physical and mental health.[13,15,18–21,23–25] For instance, by elevating the probability of short sleep, high ambient temperatures may predispose susceptible segments of society to worsened affect,[23,74] anger and aggression,[23,24] hypertension and adverse cardiovascular outcomes,[20–22] diminished cognitive performance,[15,16] elevated risk of accidents and injuries,[25] and compromised immune system functioning.[19] While further research should seek to clarify this hypothesis, addressing the nocturnal impact of rising ambient temperatures on human sleep may be an efficient early intervention to reduce downstream adverse behavioral and developmental impacts linked to insufficient sleep. Through the use of consistently measured sleep records registered by sleep-tracking wristbands, our findings indicate that elevated temperatures drive sleep loss primarily by delaying when people fall asleep, providing a specific target for future adaptive interventions that seek to attenuate the impact of nighttime heat.

Interestingly, a corollary to our results is that ambient cooling interventions may be able to promote sleep gain (Figure 2A). Although access to air conditioning may partially buffer the effect of high ambient temperatures (Figure 3C), these same adaptive technologies can potentially exacerbate the unequal burdens of both global and local warming, through increased GHG emissions and ambient heat displacement.[31,58,75,76] Moreover, continued urbanization is expected to further amplify ambient heat exposure.[77,78] Heat-resilient planning, environmental design, and biopsychosocial interventions may be needed to

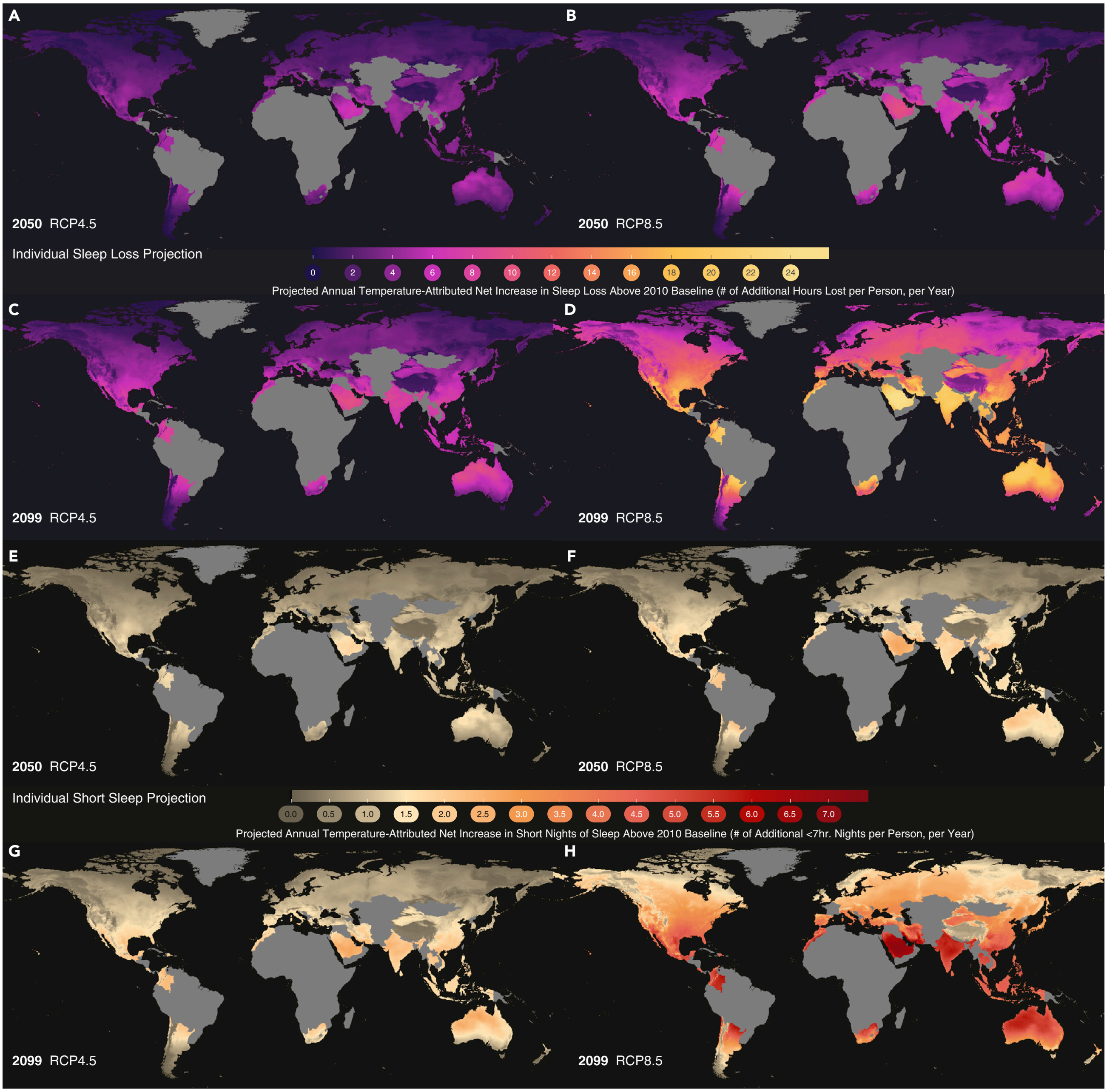


**Figure 5. Projected net sleep change from future warming**

(A–D) World maps projecting annual individual temperature-attributed net sleep loss by 2050 and 2099 (net of 2010 temperature-driven sleep loss) under intermediate (RCP4.5, left) and high GHG concentration (RCP8.5, right) scenarios. Each colored grid cell represents the additional per-person annual sleep loss projected for the corresponding 25 × 25 km area using the ensemble average of 21 NASA bias-corrected and statistically downscaled CMIP5 models. Darker purple colors represent areas with the lowest projected annual net sleep losses from the 2010 baseline, while lighter yellow colors signal areas with the largest annual sleep reductions. Projections are only shown for countries in the dataset; other countries shown in gray. Geographic inequality in the magnitude of climate-change-driven sleep loss is evident already by 2050 and becomes more pronounced by the end of the century, with global inequalities scaling with the level of future emissions.

(E–H) Global impact maps projecting the individual excess count of temperature-attributed nights of short sleep by 2050 and 2099 (net of 2010 temperature-attributed sleep loss) under a midcentury stabilized GHG concentration scenario (RCP4.5, left) and unmitigated increasing GHG concentration scenario (RCP8.5, right). Grid cells depict the additional annual number of short (<7 h) sleep nights per person for the specified 25 × 25 km area above the 2010 baseline. Brown colors indicate areas with relatively lower impacts on insufficient sleep, orange colors depict areas with moderate impacts, and red colors represent regions with more severe impacts. Planetary-scale societal sleep impacts due to ambient temperature accrue unevenly across regions and over time, with higher GHG concentrations leading to more pervasive severe impacts.

equitably protect the world's urban population centers and vulnerable communities from differential exposure to magnified nighttime temperatures.[59,79–81]

Several considerations should be taken into account when interpreting our results. First, global access and adoption of wearable devices is not geographically or demographically uniform. Our dataset contains more people who are middle-aged, male, and from high- and upper-middle-income countries (Figure 1B; Experimental procedures). Given that nighttime temperature effects are larger for females, the elderly, and lower-middle-income countries in our sample, the magnitude of our primary effect estimates and projections is likely conservative. Sleep-tracking wristband ownership may also be associated with unobserved demographic factors, including higher socioeconomic status, physiological resilience, and access to cooling technologies, possibly reducing the accuracy of our estimates—especially in lower-middle-income countries.[76]

Second, the deconvolution process used in our analyses likely mechanically biases our effect estimates toward zero.[82] Nevertheless, we observe consistent ambient-temperature effects on sleep—even for people living in industrialized societies and high-income countries with plausible access to air conditioning (Figure 3C). Moreover, station-based measures of ambient temperature may differ from actual temperature exposures where people live, likely attenuating the magnitude of our empirical estimates of the relationship between temperature and sleep.[35,39,83] As such, results from our ecological study reflect the total effect of ambient outdoor temperature on human sleep duration and timing, including all sleep-adjacent behavioral effects. For instance, temperature-altered physical activities—previously shown to be sensitive to ambient thermal conditions[55,84–87]—may subsequently impact human sleep. Indeed, in an alternative model specification where we simultaneously include maximum and minimum temperature as explanatory variables, we find that daytime maximum temperatures may result in greater sleep loss (Table S45). However, we interpret this exploratory result cautiously since the specification risks introducing multicollinearity due to serial correlation between daily minimum and maximum temperature values. Future multi-country studies with paired person-level physical activity outcomes are needed to assess whether altered physical activity may be implicated in the causal pathway linking temperature and sleep outcomes, including the delay in sleep onset that we identify.

Third, the current study primarily measures changes in sleep duration and timing, which does not convey how the observed decline in sleep duration impacts underlying sleep physiology. Controlled experiments with human subjects have shown that
Q10 Q9 rapid eye movement (REM) and non-REM (NREM) sleep decrease when people are exposed to high environmental temperatures.[37] Yet it remains unclear how ambient temperature modulates human sleep architecture and other neurobehavioral correlates of restorative sleep in real-world settings globally.[34] If people respond differently outside of the sleep laboratory, for instance, via adaptive improvements to sleep quality, then the consequences of the sleep loss we identify may be partially offset. In an initial exploratory analysis (mirroring our analytical approach outlined in Equation 1), we investigate the influence of ambient temperature on sleep interruption—the probability that an individual wakes up one or more times during the nighttime sleep period. We do not find evidence that an increase in ambient temperature significantly reduces or otherwise alters registered nighttime awakening (Table S51), suggesting that temperature-driven reductions in sleep quantity may not be compensated for with improvements in sleep quality. However, similar to wrist actigraphy, accelerometer-based activity-tracking wristbands may underestimate nighttime awakenings, suggesting that the sleep impact estimates in this study may be conservative. Future *in situ* research should further investigate whether sleep fragmentation is also sensitive to ambient weather conditions. Moreover, global research is needed to understand the impact of ambient temperature on sleep disorders[12] and coping behaviors.[88]

Fourth, although our sample includes data from 68 countries spanning all populated continents, it has sparse coverage for large parts of Africa, Central America, South America, and the Middle East—regions that already rank among the warmest in the world (Figure 5). Climate projections indicate that many of the countries within these regions will be disproportionately exposed to some of the highest ambient temperatures and most cooling degree days, warranting future study.[75]

Lastly, even though we show that rising temperatures exert larger impacts in warmer regions and do not find evidence of short-term acclimatization, it is possible that people may adapt to warmer nighttime temperatures in the future through technological or environmental developments not captured by our historical estimates, which likely already reflect considerable adaptation (Figure 3C).[89,90] To this end, future research is needed to investigate equitable policy, planning, and design innovations that alleviate the stress of elevated nighttime temperatures and promote resilient slumber on an individual, societal, and planetary scale.

## EXPERIMENTAL PROCEDURES

### Resource availability

#### *Lead contact*

Further information and requests for resources should be directed to lead author, Kelton Minor (kmi@samf.ku.dk).

#### *Materials availability*

No new materials were generated in this study.

#### *Data and code availability*

Meteorological data are publicly available from https://www.ncdc.noaa.gov/ghcn-daily-description and https://psl.noaa.gov/data/gridded/data.ncep.reanalysis2.html. Global population data are available online from https://sedac.ciesin.columbia.edu/data/set/gpw-v4-population-count-rev11. Global climate sleep projection data, analysis code, and derived model data that support the findings of this study have been deposited at Harvard Dataverse under the DOI [Link] and are publicly available as of the date of publication. Raw data Q11 are not publicly available to preserve the privacy of participants. Interested researchers may contact the corresponding authors about additional analyses.

### Data description

No statistical methods were used to predetermine sample size, consistent with recent large-scale behavioral studies employing digital trace data.[91] Datastreams from mobile activity-tracking devices hold potential utility for assessing the human impacts of global environmental changes, with a recent systematic review specifically highlighting the need for large-scale sleep studies that use wearable devices to register consistent, objective measures of sleep *in situ* across a variety of ambient conditions and climatological settings.[92,93] For our person-level analysis, we include sleep entries collected over a 2-year period from September 2015 through October 2017 from 47,628 anonymous adults who electronically consented for their data to be processed for research

Please cite this article in press as: Minor et al., Rising temperatures erode human sleep globally, One Earth (2022), https://doi.org/10.1016/j.oneear.2022.04.008

purposes. All data analyses were carried out in accordance with the EU's General Data Protection Regulation 2016/679 (GDPR) and the regulations set out by the Danish Data Protection Agency. To our knowledge, this is the largest sample of mobile sleep-tracking-device users yet employed to study the relationship between meteorological factors and human sleep. To investigate whether meteorological variables influence several sleep parameters of interest, we register the following for each subject in our dataset: the onset time when the sleep period commences (sleep onset), the midpoint of the registered sleep period (midsleep), the detected time when the sleep period ends (sleep offset), and the total sleep time registered during a given night (sleep duration).

Self-reported age, sex, height, and weight data were registered via a single cross-sectional report at the onset of participation and were aggregated into Q12 age group, sex, and World Health Organization (WHO) BMI categories during Q13 a preprocessing stage. We aggregated 10.67 billion sleep-state observations—measured in 1-min epochs—into 7.41 million sleep records. Geolocalized sleep observations were linked with nightly meteorological data from two sources. For each nighttime sleep observation, we compute the inverse distance-weighted average of nearby station-level records of minimum temperature, maximum temperature, diurnal temperature range, and precipitation data within a 100-km radius, using station measurements from the National Centers for Environmental Information Global Historical Climatology Network - Daily (GHCND) dataset. In addition, we link each observation to gridded wind speed, daily cloud cover, and relative humidity data from the National Centers for Q14 Environmental Prediction (NCEP) Reanalysis 2 project.[94,95]

### Inclusion criteria

We adopt inclusion criteria for min and max allowable sleep duration used in prior global observational sleep studies (4 h < sleep duration < 12 h).[96] To study the effect of nighttime ambient temperature on concurrent sleep attainment during the nocturnal period, we further filter sleep entries based on local timing (19:00 < sleep onset time < 08:00 and 00:00 < sleep offset time < 15:00). Our primary results are robust to using alternative sleep timing filters used in the literature instead of these wider criteria (Table S31).[96,97] Since people may compensate for insufficient sleep at night with daytime naps shorter than 4 h, we confirm that our primary results are robust to using 24-h sleep attainment instead (Table S8). To ensure sufficient temporal coverage, we require each person to have a minimum of 4 weeks (28 nights) with sleep entries and entries on at least 25% of nights spanning the period from first to last use. Our results are robust to alternative temporal inclusion criteria, including constraining our analysis to only those with greater than 56, 84, and 112 total nights with sleep entries (Table S33). Furthermore, our results persist when constraining our sample to those with regular wristband use on 50%, 75%, and 85% of nights from their date of first use (Table S32).

### Sleep measurement

The data were registered by SWR30 and SWR12 waterproof sleep-tracking wristbands that utilize an internal accelerometer to detect movement and measure sleep and wake states in 1-min epochs. The wristbands have been internally validated at temperatures exceeding those observed in the present study and have a listed operating temperature range of −20°C–60°C, well beyond the distribution of ambient temperatures encountered in this study. The sleep- and wake-state estimates produced by these sleep-tracking wristbands have been found to accurately align with independent, contemporaneous measurements of mobile-device inactivity and activity, a behavioral proxy for wakefulness.[98] Further, the external validity of sleep estimates produced by these devices has been assessed by comparing the national and demographic sleep estimates generated by the accelerometer-based wristbands to results from a suite of previously published sleep studies.[99] The resulting global dataset reproduces established socio-temporal, demographic, and geographic sleep trends. Distinct weekend-weekday differences in sleep duration are indicative of characteristic work and social schedules that constrain human sleep, with reduced sleep on weekdays and sleep recovery on weekends (Figure 1C; Table S2). For this sample of wristband users, the median individual average nighttime sleep duration was 7.1 h. A greater percentage of older adults (43.6%) regularly slept less than 7 h a night compared with young adults (32.7%), and middle-aged adults had shorter average sleep duration during the working week compared with both younger and older adults, consistent with the literature (Tables S1 and S2).[100] Previous research also suggests that average sleep duration in East Asian countries is moderately lower than in Western countries.[96,101,102] Our wearable dataset replicates these regional differences.[99] For instance, adults in Japan sleep less on both weekdays and weekends compared with adults from four different European countries, across all adult age ranges (Table S2).

### Sample characteristics

Our sample consists of people who self-selected into sleep-tracking wristband use and thus differs from background populations in both observable and unobservable ways. We observe that our sample consists of a greater proportion of males (∼69%) than females (∼31%). Further, participants in the dataset resided entirely within high- and middle-income countries. Approximately 80% of included users were from 42 different high-income countries and ∼20% were from 26 middle-income countries, with ∼2% from nine lower-middle-income countries. The sample consists primarily of middle-aged adults (25–65 years; ∼91%), with fewer young adults (19–25 years; 6%) and older adults (65+ years; 3%). The age-standardized BMI values from the top five countries with the most users in our dataset (Japan, Germany, United Kingdom, Sweden, and Spain) fall within or near the WHO population estimate ranges for these countries (Table S4). Of note, the age-standardized BMI for both men and women from Japan was slightly higher than the WHO range. We do not find evidence for heterogeneity in the effect of nighttime temperature on sleep duration across BMI categories in our dataset (Figure S5).

### Models

Our primary relationship of interest is the effect of daily nighttime minimum temperature on within-person sleep outcomes.

### Person-level multivariate flexible fixed effects panel regression

$$\begin{aligned} Y_{iktm} \; = \; & f(TMIN_{iktm}) + TMIN.NORM1981to2010_{iktm} + Z\eta + \alpha_i + \mu_t \\ & + \nu_{km} + \varepsilon_{iktm} \end{aligned} \qquad \text{(Equation 1)}$$

In this multivariate, fixed-effects panel model, $i$ indexes individuals, $k$ indexes first-level administrative division (e.g., states), $t$ indexes unique date of study, and $m$ indexes unique calendar months. Our dependent variable $Y_{iktm}$ represents the sleep duration (in minutes) of individual $i$ in a given first administrative region $k$ on date $t$ and calendar month $m$. Thus, $Y_{iktm}$ sequentially represents sleep duration (in minutes) (Figure 1A), sleep onset (Figure 1E), midsleep (Figure 1C), offset (Figure 1B), and an indicator for short sleep (using several standard threshold definitions) (Figure 1D; Tables S9–S11).[14] Our independent variable of interest is minimum nighttime temperature, $TMIN_{iktm}$. We also control for local seasonality through the inclusion of 1981–2010 days-of-year averages of minimum temperature from 1981 to 2010, $TMIN.NORM1981to2010_{iktm}$ computed for each location-night. Further, we control for daily precipitation, diurnal temperature range ($TMAX_{iktm} - TMIN_{iktm}$), percentage cloud cover, relative humidity, and average wind speed, represented via $Z\eta$, as failure to do so may bias our estimates of the effect of nighttime minimum temperature on our sleep outcome measure.[44] In Equation 1, we convert continuous meteorological variables into indicator variables for each 5°C minimum temperature bin (e.g., $f(TMIN_{iktm})$), 5°C diurnal temperature range bin,[84] 1-cm precipitation bin, 5-m/s windspeed bin, and 20 percentage point bin of cloud cover and relative humidity. This enables us to flexibly estimate a nonlinear relationship between each of our meteorological variables and sleep outcomes (Figures 2A and S1).[55] We omit the 5°C–10°C minimum temperature, 5°C–10°C diurnal temperature range, 0-cm precipitation, 0- to 5-m/s windspeed, 0% cloud cover, and 60%–80% humidity bins as reference categories. Finally, we also include climate normals within $Z\eta$ for each of our meteorological control variables, computed as the day-of-year average value from 1981 to 2010 for a given location-date using inverse distance-weighted weather station values and extracted gridded reanalysis time series. We interpret our estimates as the average within-individual change in sleep outcomes at a particular temperature bin relative to these baselines.

Unobservable person-specific, location-specific, or temporal factors may influence sleep outcomes. To ensure that these individual-specific factors

Please cite this article in press as: Minor et al., Rising temperatures erode human sleep globally, One Earth (2022), https://doi.org/10.1016/j.oneear.2022.04.008

do not bias our estimates of the effect of weather on sleep, we include $\alpha_i$—representing user-level indicator variables—in Equation 1. These variables control for all stable unobserved characteristics for each person and sleep-tracking wristband.[44] Further, there may be unobserved daily developments or region-specific seasonal changes—such as daylight—or secular trends influencing sleeping outcomes that might spuriously correlate with the weather. In order to control for these potential confounders, we include $\mu_t$ and $\nu_{km}$ in Equation 1, representing date of study (e.g., "2015-11-11" and "2016-11-11") and first admin-by-calendar month indicator variables, respectively. Our primary results are robust to alternative temporal controls, including replacing first admin-by-month with first admin-by-week indicator variables to control for administrative region-specific weekly changes (Table S30).

Our empirical identifying assumption, consistent with the climate econometrics literature,[44,103] is that the remaining variation in daily minimum temperature is as good as random after conditioning on these fixed effects.[104] The estimated model coefficients from $TMIN_{iktm}$ can thus be interpreted as the causal effect of an increase in minimum nighttime temperature on sleep duration.[45,105] We estimate Equation 1 using ordinary least squares and adjust for possible spatial and serial correlation in $\varepsilon_{iktm}$ by employing heteroskedasticity-robust standard errors clustered at the first administrative division level. We omit non-climatic control variables from Equation 1 because of their potential to generate bias in our parameters of interest.[44,106,107] Our results are consistent when binning each of our climate control variables as well (Tables S34–S36) and separately remain significant when clustering standard errors on both spatial units (first administrative region) and temporal units (date of study) (Tables S46–S48). Our flexible model results are robust to substituting the National Weather Service (NWS) Heat Index[108]—a measure of heat stress—for minimum temperature and relative humidity in Equation 1 (Figure S2B; Table S16). Our primary results persist when aggregating person-level sleep observations to the first-administrative-region-night level with mean sleep duration as the dependent variable (Tables S43 and S44). See supplemental information for a description of additional robustness checks.

The global weather data that we rely on for our primary historical estimate have a higher concentration of stations providing temperature and precipitation measurements over North America and Eurasia than over Africa and parts of South America, resulting in some exclusion of users into the final sample for our primary model and potentially less precise ambient temperature estimates for lower-middle-income countries. Our results are robust to using globally gridded reanalysis data instead, resulting in a more inclusive sample and slightly larger sleep loss estimates across the temperature distribution (Figure S2A; Tables S6–S8).[94] Importantly, the resulting empirical estimates from our analyses are likely conservative. A combination of measurement error and amplification of noise due to the deconvolution process we use in our analyses likely further biases our estimates of the relationship between temperature and sleep outcomes toward zero.[82,83,109]

## Sociodemographic and seasonal subgroup analyses

$$\begin{aligned} Y_{iktm} \;=\; & TMIN_{iktm} * \varnothing_s + TMINORM1981to2010_{iktm} + Z\eta + \alpha_i + \mu_t \\ & + \nu_{km} + \varepsilon_{iktm} \end{aligned} \qquad \text{(Equation 2)}$$

As an alternative to our primary binned specification, we also estimate a multivariate fixed-effects linear panel model, where $f()$ is replaced with a linear function (Table S8). In order to inspect the marginal effect of temperature by subgroups on our relationship of interest, we preserve this specification and sequentially interact our continuous measure for nighttime minimum temperature $TMIN_{iktm}$ with a categorical variable $\varnothing_s$, successively representing age group (Figure 3A), sex (Figure 3B), World Bank gross national income (GNI) category (Figure 3C), season of the year (Figure 3D; Table S21), and BMI group (Figure S5). We interpret the resulting estimates as the marginal effects of a 1°C minimum temperature increase on sleep loss for each subgroup relative to the corresponding reference category (Figures 3 and S5; Tables S22–S27). Since demographic category information is not available for some subjects across all subgroup categories, our sample size in these regressions varies.

## Acclimatization tests I and II: Regional climate adaptation and intra-annual adaptation

To investigate regional adaptation—whether those residing in regions with generally warmer average nighttime temperatures are differentially resilient to temperature shocks compared with those residing in colder regions—we employ this same specification with contemporaneous nighttime temperature interacted with deciles of average location-specific minimum temperature over the 2015–2017 study period (D1, coldest to D10, warmest) (Figure 3E; Table S28). To test for possible medium-term acclimatization to warmer nighttime temperatures, we extract a subset of the data consisting of the first and last summer months for each location and year of observation. Thus, for observations originating from the northern hemisphere (southern hemisphere), June (December) is labeled as the first month of summer when locally warmer temperatures are a relatively newer occurrence, while August (February) is labeled as the last month of summer when elevated temperatures have become more familiar. We employ a summer month interaction term $\varnothing_s$ in Equation 2 while otherwise keeping the same model specification. The resulting estimate represents the marginal effect of a 1°C minimum temperature increase on sleep outcomes during the last summer month compared with the first (Table S38).

## Acclimatization tests III and IV: Inter-day adaptation and intra-day adaptation

$$\begin{aligned} Y_{iktm} \;=\; & TMIN_{iktm} + TMIN_{ik(t-1)m} + TMIN\cdots_{ik(t-n)m} + TNORM_{iktm} + Z\eta \\ & + \alpha_i + \mu_t + \nu_{km} + \varepsilon_{iktm} \end{aligned} \qquad \text{(Equation 3)}$$

To investigate the lagged effects of nighttime minimum temperature on potential delayed sleep displacement or recovery, we specify a distributed lag model that includes both a contemporaneous and lagged temperature terms $TMIN_{ik(t-x)m}$ for each of the previous 7 days (Table S39). As robustness checks, we also run a version of this specification with lagged minimum temperature terms for each of the preceding 14 days and a separate specification with lagged terms for all weather variables over the previous 7 days (Table S39). To assess possible acute adaptation via intra-day substitution of nighttime sleep with daytime rest, we estimate an alternative version of our primary specification where nighttime sleep is replaced with a 24-h sleep measure (Table S8).

## Alternative temperature measure flexible fixed-effects panel regression

$$Y_{iktm} = f(TMIN.ANOMALY1981to2010_{iktm}) + Z\eta + \alpha_i + \mu_t + \nu_{km} + \varepsilon_{iktm} \qquad \text{(Equation 4)}$$

Climate change is increasing the frequency and magnitude of warmer than normal nights. As an alternative specification to Equation 1, we replace both $f(TMIN_{iktm})$ and $TMINORM1981to2010_{iktm}$ with a single term: nighttime temperature anomalies $f(TMIN.ANOMALY1981to2010_{iktm})$. This new independent variable of interest represents the nightly minimum temperature deviation from the normal historical average (from 1981 to 2010) for each subject-night (Table S18). We include 1°C flexible temperature anomaly bins to semi-parametrically estimate the relationship between nighttime minimum temperature anomalies and sleep duration. Furthermore, we add binned meteorological controls, employing the same baseline categories as specified in Equation 1. We omit the temperature anomaly reference range of $-0.5°$C–0.5°C and interpret our estimates as the average within-individual change in sleep duration within a particular nighttime temperature anomaly bin relative to this baseline bin (Figure S4; Table S19). We estimate a linear version of this specification as a further robustness check (Table S18).

## Spline regression models

To investigate how climate change may impact temperature-driven human sleep loss and the prevalence of short sleep in 2050 and 2099, we draw upon data from 21 Coupled Model Intercomparison Project Phase 5 (CMIP5) models[110] run separately under an intermediate "stabilization" scenario (RCP4.5) and increasing atmospheric GHG concentration scenario

RCP8.5[111] and extract NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP) bias-corrected, statistically downscaled, nightly temperature time series[112] for each 25 × 25 km grid cell spanning each country included in our global sleep dataset. Although RCP8.5 is increasingly viewed as a less plausible anthropogenic forcing scenario given recent decarbonization trends,[113,114] we include it for the purpose of modeling the risk associated with a "no mitigation policy" counterfactual future. Further, large uncertainties in the Earth climate system prevent ruling out large future warming if conditional and unconditional emissions pledges are not implemented.[115,116] Climate change is projected to extend the nighttime temperature distribution rightwards, resulting in extreme ambient temperatures that exceed our historical observations. Rather than assigning these extreme temperatures the fitted value from the highest temperature bin within the historical distribution, we fit a linear spline to the data—with knots placed at $-20^\circ$C and $10^\circ$C—and forecast behavioral estimates for projected temperatures for 2050 and 2099.[84] We construct spline models for both individual sleep duration and short sleep probability (Table S37). The functional forms yielded by the spline models closely mirror the relationships uncovered by Equation 1.

### Person-level annual-temperature-attributed excess sleep projection plots

To plot the projected average excess sleep loss attributed to suboptimal ambient temperature (Figure 4A), we apply our spline regression model output to extract the 2010, 2050, and 2099 average daily minimum temperature predicted sleep loss from all 21 of NASA's NEX-GDDP bias-corrected, statistically downscaled daily climate models. We sum the daily projected sleep loss and short sleep for each grid-cell and each model, yielding estimates of the projected total individual sleep impacts for each grid-cell and model combination. We then average across all global grid cells—weighting cells by their estimated 2015 human population counts (using Gridded Population of the World [GPWv4] data[117])—to compute the population-weighted average annual individual temperature-driven sleep loss and short sleep for each climate model-year (Figures 4A and 4B). We plot the distributions of all temperature-attributed individual short sleep projections, along with model-specific estimates (Figure 4B). Separately, we compute and plot country-level projected annual sleep loss (per person) by instead averaging grid cells for each country, across all 21 downscaled climate models (Figure S6).

### Grid cell annual net sleep change projection maps

To map the projected change in global sleep impacts by mid-century and end of century under different anthropogenic forcing scenarios, we separately plot the ensemble mean estimate of annual per-person temperature-attributed sleep loss (Figures 5A–5D) and short sleep (Figures 5E–5H) across all models for each grid cell. Thus, each colored grid cell represents the projected additional annual individual sleep loss (Figures 5A–5D) or short sleep (Figures 5E–5H) for a person residing within the area demarcated by that grid cell, net of the 2010 temperature-attributed excess sleep loss for the same grid cell.

## SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.oneear.2022.04.008.

## ACKNOWLEDGMENTS

Q15 We thank workshop participants at the 101st American Meteorological Society Annual Meeting for helpful comments. K.M. acknowledges support from The Danish Agency for Higher Education and Science and The Independent Research Fund Denmark (grant 9095-00007A).

## AUTHOR CONTRIBUTIONS

Conceptualization, K.M., A.B.-N., S.L., and N.O.; data structuring, K.M., A.B.-N., and S.S.J.; formal analysis, K.M. and N.O.; funding acquisition, S.L., A.B.-N., and K.M.; investigation, K.M. and N.O.; methodology, N.O. and K.M.; software, K.M., N.O., S.S.J., and A.B.-N.; visualization, K.M. and N.O.; writing – original draft, K.M.; writing – review and editing, K.M., N.O., and S.L.

## DECLARATION OF INTERESTS

The authors declare no competing interests.

Received: October 30, 2021
Revised: March 14, 2022
Accepted: April 26, 2022
Published: May 20, 2022

## REFERENCES

1. Berry, H.L., Waite, T.D., Dear, K.B.G., Capon, A.G., and Murray, V. (2018). The case for systems thinking about climate change and mental health. Nat. Clim. Change *8*, 282–290. https://doi.org/10.1038/s41558-018-0102-4.
2. Manning, C., and Clayton, S. (2018). Threats to mental health and well-being associated with climate change. In Psychology and Climate Change, S. Clayton and C. Manning, eds. (Academic Press), pp. 217–244.
3. Clayton, S., Devine-Wright, P., Stern, P.C., Whitmarsh, L., Carrico, A., Steg, L., Swim, J., and Bonnes, M. (2015). Psychological research and global climate change. Nat. Clim. Change *5*, 640–646. https://doi.org/10.1038/nclimate2622.
4. Evans, G.W. (2019). Projected behavioral impacts of global climate change. Annu. Rev. Psychol. *70*, 449–474. https://doi.org/10.1146/annurev-psych-010418-103023.
5. Park, R.J., Goodman, J., and Behrer, A.P. (2020). Learning is inhibited by heat exposure, both internationally and within the United States. Nat. Hum. Behav. *5*, 19–27. https://doi.org/10.1038/s41562-020-00959-9.
6. Burke, M., González, F., Baylis, P., Heft-Neal, S., Baysan, C., Basu, S., and Hsiang, S. (2018). Higher temperatures increase suicide rates in the United States and Mexico. Nat. Clim. Change *8*, 723–729. https://doi.org/10.1038/s41558-018-0222-x.
7. Romanello, M., McGushin, A., Di Napoli, C., Drummond, P., Hughes, N., Jamart, L., Kennard, H., Lampard, P., Solano Rodriguez, B., Arnell, N., et al. (2021). The 2021 report of the Lancet Countdown on health and climate change: code red for a healthy future. Lancet *398*, 1619–1662. https://doi.org/10.1016/S0140-6736(21)01787-6.
8. Nori-Sarma, A., Sun, S., Sun, Y., Spangler, K.R., Oblath, R., Galea, S., Gradus, J.L., and Wellenius, G.A. (2022). Association between ambient heat and risk of emergency department visits for mental health among US adults, 2010 to 2019. JAMA Psychiatry *79*, 341–349. https://doi.org/10.1001/jamapsychiatry.2021.4369.
9. Obradovich, N., and Minor, K. (2022). Identifying and preparing for the mental health burden of climate change. JAMA Psychiatry *79*, 285–286. https://doi.org/10.1001/jamapsychiatry.2021.4280.
10. Hwong, A.R., Wang, M., Khan, H., Chagwedera, D.N., Grzenda, A., Doty, B., Benton, T., Alpert, J., Clarke, D., and Compton, W.M. (2022). Climate change and mental health research methods, gaps, and priorities: a scoping review. Lancet Planet. Health *6*, e281–e291. https://doi.org/10.1016/s2542-5196(22)00012-2.
11. Obradovich, N., Migliorini, R., Mednick, S.C., and Fowler, J.H. (2017). Nighttime temperature and human sleep loss in a changing climate. Sci. Adv. *3*, e1601555. https://doi.org/10.1126/sciadv.1601555.
12. Rifkin, D.I., Long, M.W., and Perry, M.J. (2018). Climate change and sleep: a systematic review of the literature and conceptual framework. Sleep Med. Rev. *42*, 3–9. https://doi.org/10.1016/j.smrv.2018.07.007.
13. Mullins, J.T., and White, C. (2019). Temperature and mental health: evidence from the spectrum of mental health outcomes. J. Health Econ. *68*, 102240. https://doi.org/10.1016/j.jhealeco.2019.102240.
14. Hirshkowitz, M., Whiton, K., Albert, S.M., Alessi, C., Bruni, O., DonCarlos, L., Hazen, N., Herman, J., Katz, E.S., Kheirandish-Gozal, L., et al. (2015). National Sleep Foundation's sleep time duration recommendations: methodology and results summary. Sleep Health *1*, 40–43. https://doi.org/10.1016/j.sleh.2014.12.010.

Please cite this article in press as: Minor et al., Rising temperatures erode human sleep globally, One Earth (2022), https://doi.org/10.1016/j.oneear.2022.04.008

15. Killgore, W.D.S. (2010). Effects of sleep deprivation on cognition. Prog. Brain Res. *185*, 105–129.
16. Krause, A.J., Simon, E.B., Mander, B.A., Greer, S.M., Saletin, J.M., Goldstein-Piekarski, A.N., and Walker, M.P. (2017). The sleep-deprived human brain. Nat. Rev. Neurosci. *18*, 404–418. https://doi.org/10.1038/nrn.2017.55.
17. Hafner, M., Stepanek, M., Taylor, J., Troxel, W.M., and van Stolk, C. (2016). Why Sleep Matters—The Economic Costs of Insufficient Sleep (RAND Corporation).
18. Barnes, C.M., and Watson, N.F. (2019). Why healthy sleep is good for business. Sleep Med. Rev. *47*, 112–118. https://doi.org/10.1016/j.smrv.2019.07.005.
19. Irwin, M.R. (2015). Why sleep is important for health: a psychoneuroimmunology perspective. Annu. Rev. Psychol. *66*, 143–172. https://doi.org/10.1146/annurev-psych-010213-115205.
20. Cappuccio, F.P., Cooper, D., D'Elia, L., Strazzullo, P., and Miller, M.A. (2011). Sleep duration predicts cardiovascular outcomes: a systematic review and meta-analysis of prospective studies. Eur. Heart J. *32*, 1484–1492. https://doi.org/10.1093/eurheartj/ehr007.
21. Jackson, C.L., Redline, S., and Emmons, K.M. (2015). Sleep as a potential fundamental contributor to disparities in cardiovascular health. Annu. Rev. Public Health *36*, 417–440. https://doi.org/10.1146/annurev-publhealth-031914-122838.
22. Cappuccio, F.P., D'Elia, L., Strazzullo, P., and Miller, M.A. (2010). Sleep duration and all-cause mortality: a systematic review and meta-analysis of prospective studies. Sleep *33*, 585–592. https://doi.org/10.1093/sleep/33.5.585.
23. Goldstein, A.N., and Walker, M.P. (2014). The role of sleep in emotional brain function. Annu. Rev. Clin. Psychol. *10*, 679–708. https://doi.org/10.1146/annurev-clinpsy-032813-153716.
24. Bernert, R.A., Kim, J.S., Iwata, N.G., and Perlis, M.L. (2015). Sleep disturbances as an evidence-based suicide risk factor. Curr. Psychiatry Rep. *17*, 15. https://doi.org/10.1007/s11920-015-0554-4.
25. Czeisler, C.A., Wickwire, E.M., Barger, L.K., Dement, W.C., Gamble, K., Hartenbaum, N., Ohayon, M.M., Pelayo, R., Phillips, B., Strohl, K., et al. (2016). Sleep-deprived motor vehicle operators are unfit to drive: a multidisciplinary expert consensus statement on drowsy driving. Sleep Health *2*, 94–99. https://doi.org/10.1016/j.sleh.2016.04.003.
26. Yoo, S.S., Hu, P.T., Gujar, N., Jolesz, F.A., and Walker, M.P. (2007). A deficit in the ability to form new human memories without sleep. Nat. Neurosci. *10*, 385–392. https://doi.org/10.1038/nn1851.
27. Fultz, N.E., Bonmassar, G., Setsompop, K., Stickgold, R.A., Rosen, B.R., Polimeni, J.R., and Lewis, L.D. (2019). Coupled electrophysiological, hemodynamic, and cerebrospinal fluid oscillations in human sleep. Science *366*, 628–631. https://doi.org/10.1126/science.aax5440.
28. Khubchandani, J., and Price, J.H. (2019). Short sleep duration in working American adults, 2010–2018. J. Community Health *45*, 219–227. https://doi.org/10.1007/s10900-019-00731-9.
29. Ford, E.S., Cunningham, T.J., and Croft, J.B. (2015). Trends in self-reported sleep duration among US adults from 1985 to 2012. Sleep *38*, 829–832. https://doi.org/10.5665/sleep.4684.
30. Donat, M.G., Alexander, L.V., Yang, H., Durre, I., Vose, R., Dunn, R.J.H., Willett, K.M., Aguilar, E., Brunet, M., Caesar, J., et al. (2013). Updated analyses of temperature and precipitation extreme indices since the beginning of the twentieth century: the HadEX2 dataset. J. Geophys. Res. Atmos. *118*, 2098–2118. https://doi.org/10.1002/jgrd.50150.
31. Salamanca, F., Georgescu, M., Mahalov, A., Moustaoui, M., and Wang, M. (2014). Anthropogenic heating of the urban environment due to air conditioning. J. Geophys. Res. Atmos. *119*, 5949–5965. https://doi.org/10.1002/2013jd021225.
32. Obradovich, N., and Migliorini, R. (2018). Sleep and the human impacts of climate change. Sleep Med. Rev. *42*, 1–2. https://doi.org/10.1016/j.smrv.2018.09.002.
33. Schmidt, M.H. (2014). The energy allocation function of sleep: a unifying theory of sleep, torpor, and continuous wakefulness. Neurosci. Biobehav Rev. *47*, 122–153. https://doi.org/10.1016/j.neubiorev.2014.08.001.
34. Harding, E.C., Franks, N.P., and Wisden, W. (2019). The temperature dependence of sleep. Front. Neurosci. *13*, 336. https://doi.org/10.3389/fnins.2019.00336.
35. Yetish, G., Kaplan, H., Gurven, M., Wood, B., Pontzer, H., Manger, P.R., Wilson, C., McGregor, R., and Siegel, J.M. (2015). Natural sleep and its seasonal variations in three pre-industrial societies. Curr. Biol. *25*, 2862–2868. https://doi.org/10.1016/j.cub.2015.09.046.
36. Kräuchi, K. (2007). The thermophysiological cascade leading to sleep initiation in relation to phase of entrainment. Sleep Med. Rev. *11*, 439–451. https://doi.org/10.1016/j.smrv.2007.07.001.
37. Buguet, A. (2007). Sleep under extreme environments: effects of heat and cold exposure, altitude, hyperbaric pressure and microgravity in space. J. Neurol. Sci. *262*, 145–152. https://doi.org/10.1016/j.jns.2007.06.040.
38. Näyhä, S., Rintamäki, H., Donaldson, G., Hassi, J., Jousilahti, P., Laatikainen, T., Jaakkola, J.J.K., and Ikaheimo, T.M. (2014). Heat-related thermal sensation, comfort and symptoms in a northern population: the National FINRISK 2007 study. Eur. J. Public Health *24*, 620–626. https://doi.org/10.1093/eurpub/ckt159.
39. van Loenhout, J.A.F., le Grand, A., Duijm, F., Greven, F., Vink, N.M., Hoek, G., and Zuurbier, M. (2016). The effect of high indoor temperatures on self-perceived health of elderly persons. Environ. Res. *146*, 27–34. https://doi.org/10.1016/j.envres.2015.12.012.
40. Lauderdale, D.S., Knutson, K.L., Yan, L.L., Liu, K., and Rathouz, P.J. (2008). Self-reported and measured sleep duration: how similar are they? Epidemiology *19*, 838–845. https://doi.org/10.1097/ede.0b013e318187a7b0.
41. Miller, C.B., Gordon, C.J., Toubia, L., Bartlett, D.J., Grunstein, R.R., D'Rozario, A.L., and Marshall, N.S. (2015). Agreement between simple questions about sleep duration and sleep diaries in a large online survey. Sleep Health *1*, 133–137. https://doi.org/10.1016/j.sleh.2015.02.007.
42. Banks, M.A. (2020). Tech giants, armed with wearables data, are entrenching in health research. Nat. Med. *26*, 4–5. https://doi.org/10.1038/s41591-019-0701-2.
43. McNeish, D., and Kelley, K. (2019). Fixed effects models versus mixed effects models for clustered data: reviewing the approaches, disentangling the differences, and making recommendations. Psychol. Methods *24*, 20–35. https://doi.org/10.1037/met0000182.
44. Hsiang, S. (2016). Climate econometrics. Annu. Rev. Resour. Econ. *8*, 43–75. https://doi.org/10.3386/w22181.
45. Carleton, T.A., and Hsiang, S.M. (2016). Social and economic impacts of climate. Science *353*, aad9837. https://doi.org/10.1126/science.aad9837.
46. Monsivais, D., Bhattacharya, K., Ghosh, A., Dunbar, R.I.M., and Kaski, K. (2017). Seasonal and geographical impact on human resting periods. Sci. Rep. *7*, 10717. https://doi.org/10.1038/s41598-017-11125-z.
47. Lee, W., Kim, Y., Sera, F., Gasparrini, A., Park, R., Michelle Choi, H., Prifti, K., Bell, M.L., Abrutzky, R., Guo, Y., et al. (2020). Projections of excess mortality related to diurnal temperature range under climate change scenarios: a multi-country modelling study. Lancet Planet. Health *4*, e512–e521. https://doi.org/10.1016/S2542-5196(20)30222-9.
48. Lindvall, J., and Svensson, G. (2015). The diurnal temperature range in the CMIP5 models. Clim. Dyn. *44*, 405–421. https://doi.org/10.1007/s00382-014-2144-2.
49. Li, J., Vitiello, M.V., and Gooneratne, N.S. (2018). Sleep in normal aging. Sleep Med. Clin. *13*, 1–11. https://doi.org/10.1016/j.jsmc.2017.09.001.
50. Weinreich, G., Wessendorf, T.E., Pundt, N., Weinmayr, G., Hennig, F., Moebus, S., Mohlenkamp, S., Erbel, R., Jockel, K.H., Teschler, H., and Hoffmann, B. (2015). Association of short-term ozone and temperature with sleep disordered breathing. Eur. Respir. J. *46*, 1361–1369. https://doi.org/10.1183/13993003.02255-2014.

Please cite this article in press as: Minor et al., Rising temperatures erode human sleep globally, One Earth (2022), https://doi.org/10.1016/j.oneear.2022.04.008

51. Baker, F.C., Waner, J.I., Vieira, E.F., Taylor, S.R., Driver, H.S., and Mitchell, D. (2001). Sleep and 24 hour body temperatures: a comparison in young men, naturally cycling women and women taking hormonal contraceptives. J. Physiol. *530*, 565–574. https://doi.org/10.1111/j.1469-7793.2001.0565k.x.
52. Sorensen, C., Murray, V., Lemery, J., and Balbus, J. (2018). Climate change and women's health: impacts and policy directions. PLoS Med. *15*, e1002603. https://doi.org/10.1371/journal.pmed.1002603.
53. Obradovich, N., Migliorini, R., Paulus, M.P., and Rahwan, I. (2018). Empirical evidence of mental health risks posed by climate change. Proc. Natl. Acad. Sci. U S A *115*, 10953–10958. https://doi.org/10.1073/pnas.1801528115.
54. Carleton, T.A., Jina, A., Delgado, M.T., Greenstone, M., Houser, T., Hsiang, S.M., Hultgren, A., Kopp, R.E., McCusker, K.E., Nath, I.B., et al. (2020). Valuing the Global Mortality Consequences of Climate Change Accounting for Adaptation Costs and Benefits, Report No. 27599.
55. Graff Zivin, J., and Neidell, M. (2014). Temperature and the allocation of time: implications for climate change. J. Labor Econ. *32*, 1–26. https://doi.org/10.1086/671766.
56. Eban-Rothschild, A., Appelbaum, L., and de Lecea, L. (2018). Neuronal mechanisms for sleep/wake regulation and modulatory drive. Neuropsychopharmacology *43*, 937–952. https://doi.org/10.1038/npp.2017.294.
57. Hajat, S., O'Connor, M., and Kosatsky, T. (2010). Health effects of hot weather: from awareness of risk factors to effective health protection. Lancet *375*, 856–863. https://doi.org/10.1016/s0140-6736(09)61711-6.
58. Patz, J.A., Frumkin, H., Holloway, T., Vimont, D.J., and Haines, A. (2014). Climate change. JAMA *312*, 1565–1580. https://doi.org/10.1001/jama.2014.13186.
59. Watts, N., Amann, M., Arnell, N., Ayeb-Karlsson, S., Belesova, K., Boykoff, M., Byass, P., Cai, W., Campbell-Lendrum, D., Capstick, S., et al. (2019). The 2019 report of the Lancet Countdown on health and climate change: ensuring that the health of a child born today is not defined by a changing climate. Lancet *394*, 1836–1878. https://doi.org/10.1016/S0140-6736(19)32596-6.
60. Vergunst, F., and Berry, H.L. (2021). Climate change and children's mental health: a developmental perspective. Clin. Psychol. Sci. 21677026211040787. https://doi.org/10.1177/21677026211040787.
61. Liu, J., Varghese, B.M., Hansen, A., Xiang, J., Zhang, Y., Dear, K., Gourley, M., Driscoll, T., Morgan, G., Capon, A., and Bi, P. (2021). Is there an association between hot weather and poor mental health outcomes? A systematic review and meta-analysis. Environ. Int. *153*, 106533. https://doi.org/10.1016/j.envint.2021.106533.
62. Vicedo-Cabrera, A.M., Scovronick, N., Sera, F., Royé, D., Schneider, R., Tobias, A., Astrom, C., Guo, Y., Honda, Y., Hondula, D.M., et al. (2021). The burden of heat-related mortality attributable to recent human-induced climate change. Nat. Clim. Change *11*, 492–500. https://doi.org/10.1038/s41558-021-01058-x.
63. Ebi, K.L., Vanos, J., Baldwin, J.W., Bell, J.E., Hondula, D.M., Errett, N.A., Hayes, K., Reid, C.E., Saha, S., Spector, J., and Berry, P. (2021). Extreme weather and climate change: population health and health system implications. Annu. Rev. Public Health *42*, 293–315. https://doi.org/10.1146/annurev-publhealth-012420-105026.
64. Middleton, J., Cunsolo, A., Jones-Bitton, A., Wright, C.J., and Harper, S.L. (2020). Indigenous mental health in a changing climate: a systematic scoping review of the global literature. Environ. Res. Lett. *15*, 053001. https://doi.org/10.1088/1748-9326/ab68a9.
65. Baylis, P., Obradovich, N., Kryvasheyeu, Y., Chen, H., Coviello, L., Moro, E., Cebrian, M., and Fowler, J.H. (2018). Weather impacts expressed sentiment. PLoS One *13*, e0195750. https://doi.org/10.1371/journal.pone.0195750.
66. Parks, R.M., Bennett, J.E., Tamura-Wicks, H., Kontis, V., Toumi, R., Danaei, G., and Ezzati, M. (2020). Anomalously warm temperatures are associated with increased injury deaths. Nat. Med. *26*, 65–70. https://doi.org/10.1289/isee.2020.virtual.p-0410.
67. Zhang, P., Deschenes, O., Meng, K., and Zhang, J. (2018). Temperature effects on productivity and factor reallocation: evidence from a half million Chinese manufacturing plants. J. Environ. Econ. Manag. *88*, 1–17. https://doi.org/10.1016/j.jeem.2017.11.001.
68. Dasgupta, S., van Maanen, N., Gosling, S.N., Piontek, F., Otto, C., and Schleussner, C.F. (2021). Effects of climate change on combined labour productivity and supply: an empirical, multi-model study. Lancet Planet. Health *5*, e455–e465. https://doi.org/10.1016/s2542-5196(21)00170-4.
69. Park, R.J., Goodman, J., Hurwitz, M., and Smith, J. (2020). Heat and learning. Am. Econ. J. Econ. Policy *12*, 306–339. https://doi.org/10.1257/pol.20180612.
70. Lu, P., Zhao, Q., Xia, G., Xu, R., Hanna, L., Jiang, J., Li, S., and Guo, Y. (2021). Temporal trends of the association between ambient temperature and cardiovascular mortality: a 17-year case-crossover study. Environ. Res. Lett. *16*, 045004. https://doi.org/10.1088/1748-9326/abab33.
71. Wang, J., Obradovich, N., and Zheng, S. (2020). A 43-million-person investigation into weather and expressed sentiment in a changing climate. One Earth *2*, 568–577. https://doi.org/10.1016/j.oneear.2020.05.016.
72. Baylis, P. (2020). Temperature and temperament: evidence from twitter. J. Public Econ. *184*, 104161. https://doi.org/10.1016/j.jpubeco.2020.104161.
73. Garg, T., Jagnani, M., and Taraz, V. (2020). Temperature and human capital in India. J. Assoc. Environ. Resour. Econ. *7*, 1113–1150. https://doi.org/10.1086/710066.
74. Minkel, J.D., Banks, S., Htaik, O., Moreta, M.C., Jones, C.W., McGlinchey, E.L., Simpson, N.S., and Dinges, D.F. (2012). Sleep deprivation and stressors: evidence for elevated negative affect in response to mild stressors when sleep deprived. Emotion *12*, 1015–1020. https://doi.org/10.1037/a0026871.
75. Biardeau, L.T., Davis, L.W., Gertler, P., and Wolfram, C. (2020). Heat exposure and global air conditioning. Nat. Sustain. *3*, 25–28. https://doi.org/10.1038/s41893-019-0441-9.
76. Davis, L.W., and Gertler, P.J. (2015). Contribution of air conditioning adoption to future energy use under global warming. Proc. Natl. Acad. Sci. U S A *112*, 5962–5967. https://doi.org/10.1073/pnas.1423558112.
77. Tuholske, C., Caylor, K., Funk, C., Verdin, A., Sweeney, S., Grace, K., Peterson, P., and Evans, T. (2021). Global urban population exposure to extreme heat. Proc. Natl. Acad. Sci. U S A *118*. e2024792118. https://doi.org/10.1073/pnas.2024792118.
78. Wang, J., Chen, Y., Liao, W., He, G., Tett, S.F.B., Yan, Z., Zhai, P., Feng, J., Ma, W., Huang, C., and Hu, Y. (2021). Anthropogenic emissions and urbanization increase risk of compound hot extremes in cities. Nat. Clim. Change *11*, 1084–1089. https://doi.org/10.1038/s41558-021-01196-2.
79. Hoffman, J.S., Shandas, V., and Pendleton, N. (2020). The effects of historical housing policies on resident exposure to intra-urban heat: a study of 108 US urban areas. Climate *8*, 12. https://doi.org/10.3390/cli8010012.
80. Schell, C.J., Dyson, K., Fuentes, T.L., Des Roches, S., Harris, N.C., Miller, D.S., Woelfle-Erskine, C.A., and Lambert, M.R. (2020). The ecological and evolutionary consequences of systemic racism in urban environments. Science *369*, 6510. https://doi.org/10.1126/science.aay4497.
81. Nardone, A., Rudolph, K.E., Morello-Frosch, R., Casey, J.A., and Casey Joan, A. (2021). Redlines and greenspace: the relationship between historical redlining and 2010 greenspace across the United States. Environ. Health Perspect. *129*, 017006. https://doi.org/10.1289/ehp7495.
82. Blanc, E., and Schlenker, W. (2017). The use of panel models in assessments of climate impacts on agriculture. Rev. Environ. Econ. Pol. *11*, 258–279. https://doi.org/10.1093/reep/rex016.

83. Hausman, J. (2001). Mismeasured variables in econometric analysis: problems from the right and problems from the left. J. Econ. Perspect. *15*, 57–67. https://doi.org/10.1257/jep.15.4.57.

84. Obradovich, N., and Fowler, J.H. (2017). Climate change may alter human physical activity patterns. Nat. Hum. Behav. *1*, 1–7. https://doi.org/10.1038/s41562-017-0097.

85. Heaney, A.K., Carrión, D., Burkart, K., Lesk, C., and Jack, D. (2019). Climate change and physical activity: estimated impacts of ambient temperatures on bikeshare usage in New York city. Environ. Health Perspect. *127*, 037002. https://doi.org/10.1289/ehp4039.

86. Chan, N.W., and Wichman, C.J. (2020). Climate change and recreation: evidence from North American cycling. Environ. Resour. Econ. *76*, 119–151. https://doi.org/10.1007/s10640-020-00420-5.

87. Bernard, P., Chevance, G., Kingsbury, C., Baillot, A., Romain, A.J., Molinier, V., Gadais, T., and Dancause, K.N. (2021). Climate change, physical activity and sport: a systematic review. Sports Med. *51*, 1041–1059. https://doi.org/10.1007/s40279-021-01439-4.

88. Min, K b, Lee, S., and Min, J.Y. (2020). High and low ambient temperature at night and the prescription of hypnotics. Sleep *44*, zssa262. https://doi.org/10.1093/sleep/zsaa262.

89. Vicedo-Cabrera, A.M., Sera, F., Guo, Y., Chung, Y., Arbuthnott, K., Tong, S., Tobias, A., Lavigne, E., de Sousa Zanotti Stagliorio Coelho, M., Hilario Nascimento Saldiva, P., et al. (2018). A multi-country analysis on potential adaptive mechanisms to cold and heat in a changing climate. Environ. Int. *111*, 239–246. https://doi.org/10.1016/j.envint.2017.11.006.

90. Nicol, F. (2019). Temperature and sleep. Energy Build *204*, 109516. https://doi.org/10.1016/j.enbuild.2019.109516.

91. Rafaeli, A., Ashtar, S., and Altman, D. (2019). Digital traces: new data, resources, and tools for psychological-science research. Curr. Dir. Psychol. Sci. *28*, 560–566. https://doi.org/10.1177/0963721419861410.

92. Ford, J.D., Tilleard, S.E., Berrang-Ford, L., Araos, M., Biesbroek, R., Lesnikowski, A.C., MacDonald, G.K., Hsu, A., Chen, C., and Bizikova, L. (2016). Big data has big potential for applications to climate change adaptation. Proc. Natl. Acad. Sci. U S A *113*, 10729–10732. https://doi.org/10.1073/pnas.1614023113.

93. Lu, X., Wrathall, D.J., Sundsøy, P.R., Nadiruzzaman, M.D., Wetter, E., Iqbal, A., Qureshi, T., Tatem, A., Canright, G., Engo-Monsen, K., and Bengtsson, L. (2016). Unveiling hidden migration and mobility patterns in climate stressed regions: a longitudinal study of six million anonymous mobile phone users in Bangladesh. Glob. Environ. Change *38*, 1–7. https://doi.org/10.1016/j.gloenvcha.2016.02.002.

94. Kanamitsu, M., Ebisuzaki, W., Woollen, J., Yang, S.K., Hnilo, J.J., Fiorino, M., and Potter, G.L. (2002). NCEP–DOE AMIP-II reanalysis (R-2). Bull. Am. Meteorol. Soc. *83*, 1631–1643. https://doi.org/10.1175/bams-83-11-1631(2002)083<1631:nar>2.3.co;2.

95. Menne, M.J., Durre, I., Vose, R.S., Gleason, B.E., and Houston, T.G. (2012). An overview of the global historical climatology network-daily database. J. Atmos. Ocean Technol. *29*, 897–910. https://doi.org/10.1175/jtech-d-11-00103.1.

96. Walch, O.J., Cochran, A., and Forger, D.B. (2016). A global quantification of "normal" sleep schedules using smartphone data. Sci. Adv. *2*, e1501705. https://doi.org/10.1126/sciadv.1501705.

97. Althoff, T., Horvitz, E., White, R.W., and Zeitzer, J. (2017). Harnessing the web for population-scale physiological sensing: a case study of sleep and performance. In WWW '17: Proceedings of the 26th International Conference on World Wide Web (ACM Press), pp. 113–122.

98. Cuttone, A., Bækgaard, P., Sekara, V., Jonsson, H., Larsen, J.E., and Lehmann, S. (2017). SensibleSleep: a bayesian model for learning sleep patterns from smartphone events. PLoS One *12*, e0169901. https://doi.org/10.1371/journal.pone.0169901.

99. Jonasdottir, S.S., Minor, K., and Lehmann, S. (2020). Gender differences in nighttime sleep patterns and variability across the adult lifespan: a global-scale wearables study. Sleep *44*, zsaa169. https://doi.org/10.1093/sleep/zsaa169.

100. Roenneberg, T., Allebrandt, K.V., Merrow, M., and Vetter, C. (2012). Social jetlag and obesity. Curr. Biol. *22*, 939–943. https://doi.org/10.1016/j.cub.2012.03.038.

101. Ong, J.L., Tandi, J., Patanaik, A., Lo, J.C., and Chee, M.W.L. (2019). Large-scale data from wearables reveal regional disparities in sleep patterns that persist across age and sex. Sci. Rep. *9*, 3415. https://doi.org/10.1038/s41598-019-40156-x.

102. Lo, J.C., Leong, R.L.F., Loh, K.K., Dijk, D.J., and Chee, M.W.L. (2014). Young Adultsâ€™ sleep duration on work days: differences between East and west. Front. Neurol. *5*, 81. https://doi.org/10.3389/fneur.2014.00081.

103. Hsiang, S., Kopp, R., Jina, A., Rising, J., Delgado, M., Mohan, S., Rasmussen, D.J., Muir-Wood, R., Wilson, P., Oppenheimer, M., et al. (2017). Estimating economic damage from climate change in the United States. Science *356*, 1362–1369. https://doi.org/10.1126/science.aal4369.

104. Obradovich, N., Tingley, D., and Rahwan, I. (2018). Effects of environmental stressors on daily governance. Proc. Natl. Acad. Sci. U S A *115*, 8710–8715. https://doi.org/10.1073/pnas.1803765115.

105. Burke, M., Hsiang, S.M., and Miguel, E. (2015). Global non-linear effect of temperature on economic production. Nature *527*, 235–239. https://doi.org/10.1038/nature15725.

106. Hsiang, S.M., Burke, M., and Miguel, E. (2013). Quantifying the influence of climate on human conflict. Science *341*, 6151. https://doi.org/10.1126/science.1235367.

107. Acharya, A., Blackwell, M., and Sen, M. (2016). Explaining causal findings without bias: detecting and assessing direct effects. Am. Polit. Sci. Rev. *110*, 512–529. https://doi.org/10.1017/s0003055416000216.

108. Buzan, J.R., Oleson, K., and Huber, M. (2015). Implementation and comparison of a suite of heat stress metrics within the Community Land Model version 4.5. Geosci. Model Dev. *8*, 151–170. https://doi.org/10.5194/gmd-8-151-2015.

109. Obradovich, N., and Rahwan, I. (2019). Risk of a feedback loop between climatic warming and human mobility. J. R. Soc. Interface *16*, 20190058. https://doi.org/10.1098/rsif.2019.0058.

110. Taylor, K.E., Stouffer, R.J., and Meehl, G.A. (2012). An overview of CMIP5 and the experiment design. Bull. Am. Meteorol. Soc. *93*, 485–498. https://doi.org/10.1175/bams-d-11-00094.1.

111. Riahi, K., Rao, S., Krey, V., Cho, C., Chirkov, V., Fischer, G., Kindermann, G., Nakicenovic, N., and Rafaj, P. (2011). RCP 8.5—a scenario of comparatively high greenhouse gas emissions. Clim. Change *109*, 33–57. https://doi.org/10.1007/s10584-011-0149-y.

112. Thrasher, B., Maurer, E.P., McKellar, C., and Duffy, P.B. (2012). Technical Note: bias correcting climate model simulated daily temperature extremes with quantile mapping. Hydrol. Earth Syst. Sci. *16*, 3309–3314. https://doi.org/10.5194/hess-16-3309-2012.

113. Moore, F.C., Lacasse, K., Mach, K.J., Shin, Y.A., Gross, L.J., and Beckage, B. (2022). Determinants of emissions pathways in the coupled climate–social system. Nature *603*, 103–111. https://doi.org/10.1038/s41586-022-04423-8.

114. Pielke Jr, R., Burgess, M.G., and Ritchie, J. (2022). Plausible 2005–2050 emissions scenarios project between 2 °C and 3 °C of warming by 2100. Environ. Res. Lett. *17*, 024027. https://doi.org/10.1088/1748-9326/ac4ebf.

115. Hausfather, Z., and Moore, F.C. (2022). Net-zero commitments could limit warming to below 2 °C. Nature *604*, 247–248. https://doi.org/10.1038/d41586-022-00874-1.

116. Meinshausen, M., Lewis, J., McGlade, C., Gütschow, J., Nicholls, Z., Burdon, R., Cozzi, L., and Hackmann, B. (2022). Realization of Paris Agreement pledges may limit warming just below 2 °C. Nature *604*, 304–309. https://doi.org/10.1038/s41586-022-04553-z.

117. Doxsey-Whitfield, E., MacManus, K., Adamo, S.B., Pistolesi, L., Squires, J., Borkovska, O., and Baptista, S.R. (2015). Taking advantage of the improved availability of census data: a first look at the gridded population of the world, version 4. Pap. Appl. Geogr. *1*, 226–234. https://doi.org/10.1080/23754931.2015.1014272.