CLIMATE CHANGE

Nighttime temperature and human sleep loss in a changing climate

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Human sleep is highly regulated by temperature. Might climate change—through increases in nighttime heat—disrupt sleep in the future? We conduct the inaugural investigation of the relationship between climatic anomalies, reports of insufficient sleep, and projected climate change. Using data from 765,000 U.S. survey respondents from 2002 to 2011, coupled with nighttime temperature data, we show that increases in nighttime temperatures amplify self-reported nights of insufficient sleep. We observe the largest effects during the summer and among both lower-income and elderly respondents. We combine our historical estimates with climate model projections and detail the potential sleep impacts of future climatic changes. Our study represents the largest ever investigation of the relationship between sleep and ambient temperature and provides the first evidence that climate change may disrupt human sleep.

INTRODUCTION

Sleep is vital for healthy human functioning. Yet, approximately one-third of adults report sleep difficulties, making insufficient sleep a pressing public health issue (*1*). Too little sleep increases susceptibility to disease and chronic illness (*2*, *3*) and harms psychological and cognitive functioning (*4*, *5*). Both body temperature (*6*, *7*) and ambient temperature (*8*, *9*) significantly influence sleep patterns.

Regular and sufficient sleep serves a crucial role in maintaining and restoring the human body. At a physiological level, sleep loss can undercut the neural consolidation of new knowledge (*10*), the repair of skeletal muscles (*11*), and the efficient removal of waste from the brain (*12*). Insufficient sleep may also compromise immune system functioning (*13*), dysregulate metabolism (*14*), and increase systemic inflammation in the body (*15*). The subsequent health impacts of too little sleep are numerous, including increased risk for cardiovascular disease (*3*), diabetes (*2*), and obesity (*16*). From a neuropsychiatric standpoint, acute sleep deprivation is linked to worse mood (*17*), and sleep problems may contribute to the development of depression (*4*) and suicidality (*18*). Moreover, restricted sleep harms cognitive performance via reductions in memory, attention, and processing speed (*5*). Human well-being suffers without adequate rest.

Of the factors affecting sleep, temperature plays an integral role. Normal sleep-wake cycles are governed by circadian rhythms—automatic biological processes that follow a 24-hour clock—and thermoregulation is a critical determinant of both falling asleep and staying asleep (*6*). As the body prepares for sleep, dilation of blood vessels in the skin facilitates heat loss, producing an important signal for sleep onset: a decrease in core body temperature. This core temperature decrease is preceded by amplification of temperature at distal sites (for example, the hands and feet). The ratio of distal to proximal skin temperature is highly predictive of sleep onset (*19*), suggesting that heat loss from distal skin temperature regions helps to cool the core in the evening and early morning (*20*). Once core body temperature drops to produce sleep onset, it remains low throughout the night and rises again shortly before awakening. By affecting circadian thermoregulation, ambient temperatures can interrupt the normal physiology of sleep (*21*). Previous laboratory-based studies have found that exposure to elevated temperatures can prevent core body heat shedding (*9*) and that poor sleep is associated with elevated core body temperature (*7*).

Here, we report on the effect of increases in nighttime temperatures on reported nights of insufficient sleep of 765,000 U.S. residents spanning the period of 2002 to 2011. Using these data, we examine four questions. First, have atypically high nighttime temperatures harmed individuals' reported sleep quality? Second, do the effects of nighttime temperatures on sleep vary by season? Third, are the effects most acute among those least able to cope with anomalous nighttime heat? Finally, might nighttime warming due to climate change increase the incidence of insufficient sleep in the future?

RESULTS

Main effect

To investigate whether anomalous nighttime temperatures harmed the sleep quality of individuals, we constructed a data set of individuals' reported monthly nights of insufficient sleep linked with monthly historical nighttime temperature data. Our individual response data come from the Centers for Disease Control and Prevention Behavioral Risk Factor Surveillance Survey (BRFSS) pooled over the period 2002–2011. Randomly selected respondents answered the question: "During the past 30 days, for about how many days have you felt you did not get enough rest or sleep?"

Questions from the BRFSS have been assessed for validity (*22*) and reliability (*23*) and are largely consistent with other health-related activity measures, including our specific measure of perceived sleep insufficiency (*24*). Further, this specific question is used in widely cited public health studies related to sleep (*25*).

We combine these individual responses—marked by interview date and geolocated to the city level—with station-level daily temperature and precipitation and climate normals data from the National Centers for Environmental Information Global Historical Climatology Network–Daily (GHCN-D) (see Cities and Stations in the Supplementary Materials) (*26*). Notably, our analysis is robust to the use of gridded daily weather data from the PRISM Climate Group instead (see PRISM Data

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in the Supplementary Materials) (*27*). Our theoretical relationship of interest is the effect of nighttime temperature anomalies on insufficient sleep. We empirically model this relationship as

$$Y_{ijst} = \beta X_{jst} + Z\eta + \gamma_t + \nu_{js} + \epsilon_{ijst} \tag{1}$$

where β is our parameter of interest. In this pooled cross-sectional model, *i* indexes individuals, *j* indexes cities, *s* indexes seasons, and *t* indexes calendar days (our results are robust to the use of a negative binomial model instead; see Negative Binomial in the Supplementary Materials). Our dependent variable Y_{ijst} represents respondents' number of nights of insufficient sleep over the past 30 days (results are robust to dichotomizing this variable in a linear probability model; see Linear Probability Model in the Supplementary Materials). Our independent variable of interest, X_{jst}, represents the 30-day average of daily minimum temperature deviations from their normal daily values (from 1981 to 2010) over the same 30-day window as respondents' reported nights of insufficient sleep

$$X_{jst} = \frac{1}{30}\sum_{r=t-30}^{t} \mathrm{TMIN}_{jsr} - \mathrm{TMIN.NORM}_{jsr1981-2010} \tag{2}$$

where *r* indexes the days before an individual's survey response date.

The $Z\eta$ term in Eq. 1 represents a set of climatic control variables that include average temperature range, precipitation anomalies, cloud cover, and humidity [with cloud cover and humidity data drawn from the National Centers for Environmental Prediction (NCEP) Reanalysis 2 project (*28*)]. We included these other meteorological variables because their exclusion might bias our estimates of the effect of nighttime temperature anomalies (although the magnitude of β is largely unaffected by the exclusion of these variables; see Main Effect in the Supplementary Materials) (*29*).

Further, unobserved characteristics may influence sleep. For example, people may sleep better in cities with lower noise pollution or higher prevalence of air conditioning, on days when they are more likely to have leisure time, or because of other city-specific seasonal factors. To be sure that geographic and temporal factors like these do not interfere with our estimate of the effect of nighttime temperature on human sleep, we included γ_t, and ν_{js} in Eq. 1. These terms represent calendar date and city-by-season indicator variables that account for unobserved characteristics constant across cities and days as well as seasonal factors that might vary differentially by city (*30*). Notably, our results are robust to varying the specification of these controls (see Time and Location Controls in the Supplementary Materials). Our empirical identifying assumption, consistent with the literature (*31–33*), is that temperature anomalies are as good as random after conditioning on these fixed effects. The estimated model coefficient β can thus be interpreted as the effect of temperature anomalies on reports of insufficient sleep (*34–36*).

Because our estimation procedure uses exogenous city-level variations in nightly temperature deviations to predict individual-level outcomes, we account for within-city and within-day clustering of standard errors by using heteroskedasticity robust errors clustered on both city and day. Finally, we omit nonclimatic control variables from Eq. 1 because of their potential to generate bias—a phenomenon known as a "bad control" (*36*)—in our parameter of interest (nonetheless, our results are robust to the inclusion of common demographic covariates; see Demographic Controls in the Supplementary Materials).

As can be seen in Fig. 1, as temperature anomalies become more positive, the incidence of nights with insufficient sleep increases. The results of estimating Eq. 1 indicate that a +1°C deviation in nighttime temperatures produces an increase of approximately three nights of insufficient sleep per 100 individuals per month ($\beta = 0.028$, $P = 0.014$, $n = 766{,}761$). Notably, nonlinear specifications of nighttime temperatures, precipitation, and daily temperature range return similar estimates of β, and a permutation test further supports our statistical inference (see Main Effect and Permutation Test in the Supplementary Materials) (*37*). Putting scale to the magnitude of our estimated effect, a harmonized +1°C nighttime temperature anomaly, if extrapolated across the current population of the United States, would produce nearly 9 million additional nights of insufficient sleep per month or approximately 110 million extra nights of insufficient sleep annually.

Heterogeneous effects of nighttime temperature on sleep

The above β represents an estimate of the average effect of anomalous nighttime temperatures on sleep over the course of a full year. However, because excessive heat disrupts sleep by preventing normal decreases in core body temperature (*9*, *21*, *38*), above-average summer nighttime temperatures might plausibly harm sleep more than above-average temperatures in cooler periods of the year. This leads us to our second question: Do the effects of nighttime temperatures on sleep vary by season?

To investigate this question, we stratify our sample and examine Eq. 1 for each season of the year (excluding city-by-season indicator variables). We find that the effect size β during summer ($\beta = 0.073$, $P = 0.019$, $n = 179{,}117$) is almost three times the magnitude of the effects observed during any other season of the year, as can be seen in Fig. 2A. The effects during spring, fall, and winter are all positive but are smaller in magnitude and fail to gain significance at the $\alpha = 0.05$ level.

In addition to heterogeneous effects by season, we may expect that not all individuals will be similarly affected by anomalous increases in

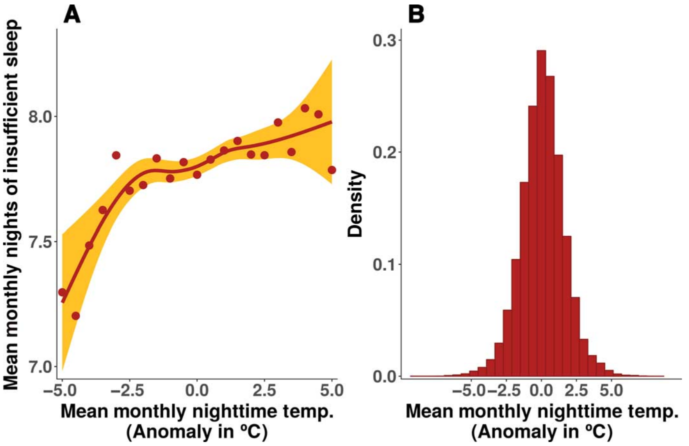

Fig. 1. Nights of insufficient sleep increase with nighttime temperature anomalies. (**A**) Relationship between average monthly nighttime temperature anomalies and 765,000 respondents' reported number of monthly nights with insufficient sleep from 2002 to 2011. As temperature anomalies become more positive, nights with insufficient sleep become more frequent. Points represent the average of respondents' monthly number of nights with insufficient sleep for each 0.5°C nighttime temperature anomaly bin. The line represents a smoothing of the raw data using a cubic spline fit. Shaded error bounds represent the 95% confidence interval of this fit. (**B**) Distribution of 2002–2011 average monthly nighttime temperature anomalies from the daily nighttime temperature normals of 1981–2010.

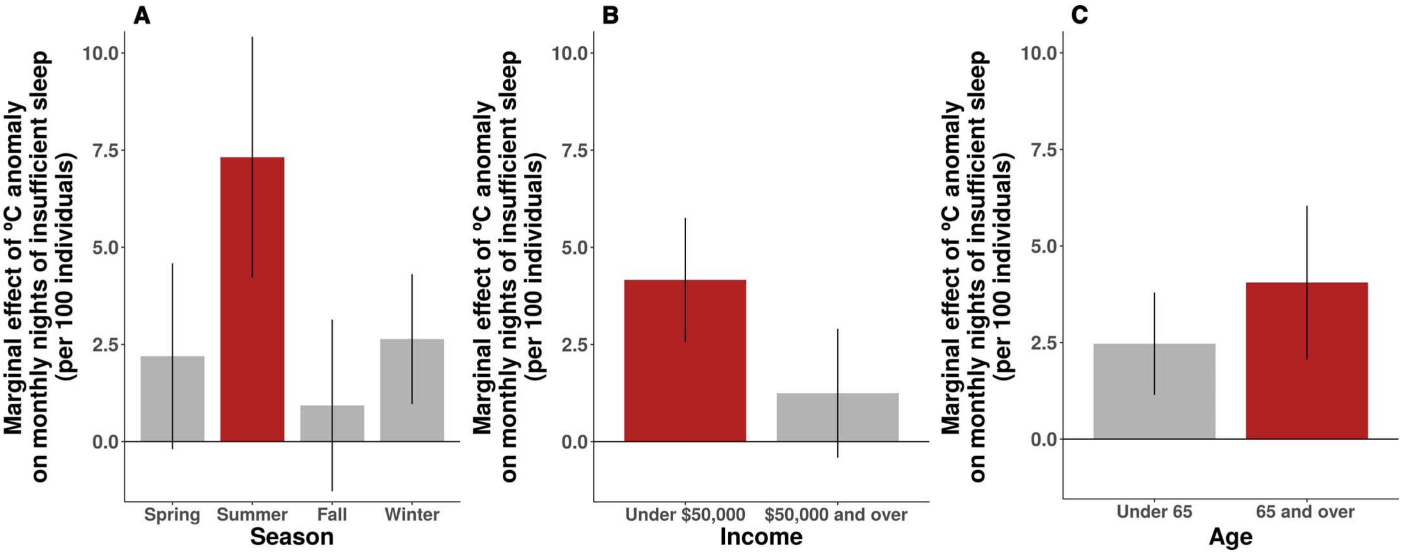

Fig. 2. The effect of nighttime temperature anomalies is most acute during the summer and among lower-income respondents and the elderly. (**A**) Marginal effects from our main model specification run on samples stratified by season (rescaled to an effect per 100 individuals). The effects observed in the summertime sample are over double the magnitude of those observed in other seasons. (**B**) Marginal effects associated with splitting the sample by median income. Those with under $50,000 per year have notably higher responses to nighttime temperature anomalies. (**C**) Sample by age, showing that the effects of nighttime temperature anomalies on sleep are larger in the elderly. Marginal effects significantly different from zero at the $\alpha = 0.05$ level are presented in red. Error bars are SEM (see regression tables in the Supplementary Materials).

nighttime temperatures. This leads us to our third question: Are the observed effects most acute among those least able to cope with nighttime heat? For example, more wealthy individuals may be able to afford running the air conditioning at night, whereas those in lower-income brackets may not (*39*). Further, it has been observed that older individuals can have deficient thermoregulation (*40*), which may make their sleep cycles more vulnerable to anomalous temperatures.

To examine whether lower-income and elderly respondents are most acutely disturbed by above-average nighttime heat, we stratify our sample along relevant demographic covariates, again estimating Eq. 1 for each subsample. Splitting the sample along its median income bracket ($50,000), we find that the effect of temperature anomalies on insufficient sleep is greatest for lower-income respondents (see Fig. 2B). The effect for the lower-income group ($\beta = 0.042$, $P = 0.009$, $n = 342{,}565$) is over three times the magnitude of the higher-income group ($\beta = 0.012$, $P = 0.455$, $n = 322{,}044$). Next, splitting the sample along a common age dimension—over or under 65 years of age—we find that our effects in older adults ($\beta = 0.041$, $P = 0.043$, $n = 223{,}211$) are nearly twice the magnitude of those found in younger adults ($\beta = 0.025$, $P = 0.064$, $n = 535{,}968$) (see Fig. 2C).

Combining these insights, the effect observed in a subsample of elderly, lower-income respondents during the summer ($\beta = 0.175$, $P = 0.007$, $n = 30{,}532$) is approximately 10 times the magnitude of the effect observed in the remainder of the sample excluding this group ($\beta = 0.018$, $P = 0.089$, $n = 735{,}743$). Thus, our data suggest that both lower-income and elderly individuals may be most susceptible to increasing nightly temperatures and that these individuals experience more severe sleep disruptions in response to atypically warm summer nights.

Potential implications of climate change for human sleep

Our historical data indicate that past nighttime temperature anomalies have likely altered historical sleep patterns in meaningful ways. In the future, climate change is likely to produce an increased frequency of above-average nighttime temperatures (see Fig. 3A) (*41*), and observed nighttime temperatures have been increasing more rapidly than daytime temperatures over the last century (*42*). These observations lead us to our fourth question: Might warming nighttime temperatures due to climate change increase the incidence of insufficient sleep in the future?

To examine this question, we calculate projected nighttime temperature anomalies for 2050 and 2099 from NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP) bias-corrected, statistically downscaled (to 25 km × 25 km), nightly temperature projections (*43*) drawn from 21 of the Coupled Model Intercomparison Project Phase 5 (CMIP5) models (*44*) run on the Representative Concentration Pathways "high emissions" scenario (RCP8.5) (*45*). We extract the projections' time series for the grid cells associated with each city and couple these predicted anomalies with our historical estimate of the relationship between nighttime temperature anomalies and insufficient sleep—β from Eq. 1—to calculate a forecast of possible insufficient sleep due to future nighttime warming at the city level for each downscaled climate model. We define our forecast of the increase in insufficient nights of sleep due to climate change by 2050 (ΔY_{mj2050}) as

$$\Delta Y_{mj2050} = \beta(\overline{X_{mjt2050} - X_{mjt2010}}) \tag{3}$$

and for the additional effect from 2050 to 2099 (ΔY_{mj2099}) as

$$\Delta Y_{mj2099} = \beta(\overline{X_{mjt2099} - X_{mjt2050}}) \tag{4}$$

where m indexes the 21 specific climate models, j indexes the city, and t indexes the day. X_{mjt}—our measure of 30-day nighttime temperature anomalies—is calculated as in Eq. 2, using 1981–2010 as the baseline. This forecasting procedure enables us to incorporate uncertainty regarding

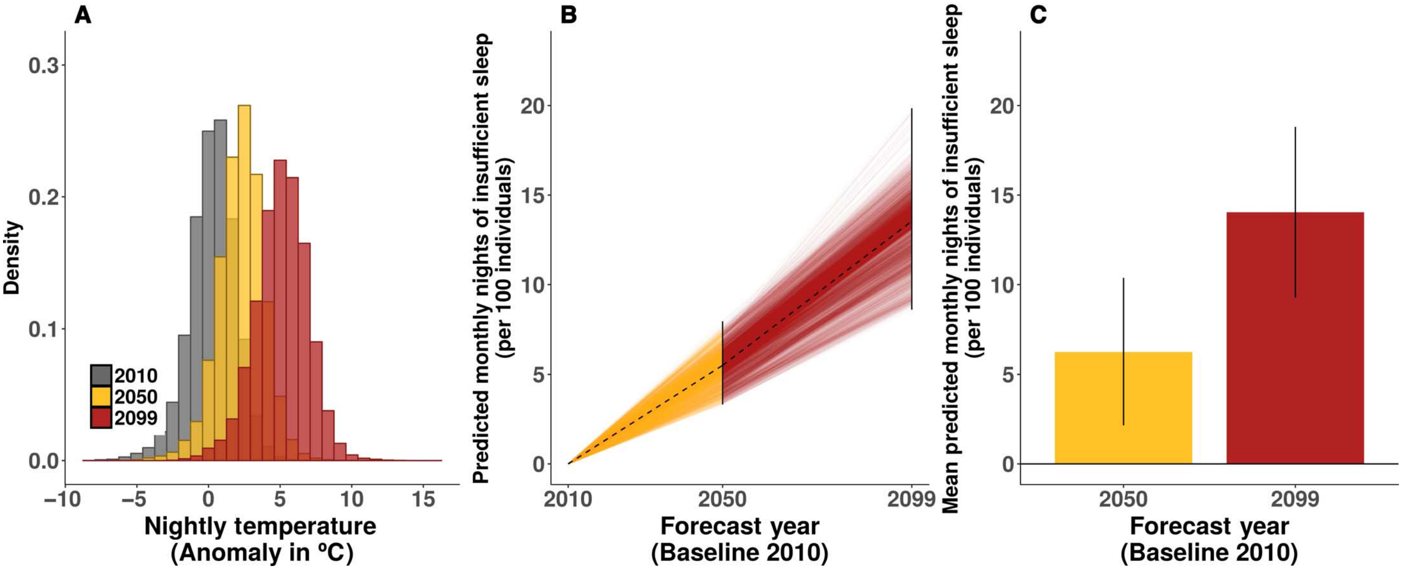

Fig. 3. Climate change may amplify human sleep loss. (**A**) Distributions of nighttime temperature anomalies calculated from 21 downscaled climate models for the cities in our sample in 2010, 2050, and 2099. Nighttime temperature anomalies from the 1981–2010 city nighttime temperature normals increase in both magnitude and variation by 2050 and 2099 as compared to 2010. (**B**) City-level forecasts for the impact of climate change on monthly nights of insufficient sleep per 100 individuals. To incorporate downscaled climate model uncertainty, we calculate an estimated change for an ensemble of 21 climatic models for 219 cities, producing nearly 4600 estimates for both 2050 and 2099. The change between 2010 and 2050 is represented by golden lines, whereas the predicted change between 2050 and 2099 is represented by red lines. The black dashed lines plot the median predicted change between each period. (**C**) Mean predicted change in sleep for each period across all climate models (rescaled to an effect per 100 individuals). Error bars are SEM and incorporate downscaled climate model uncertainty.

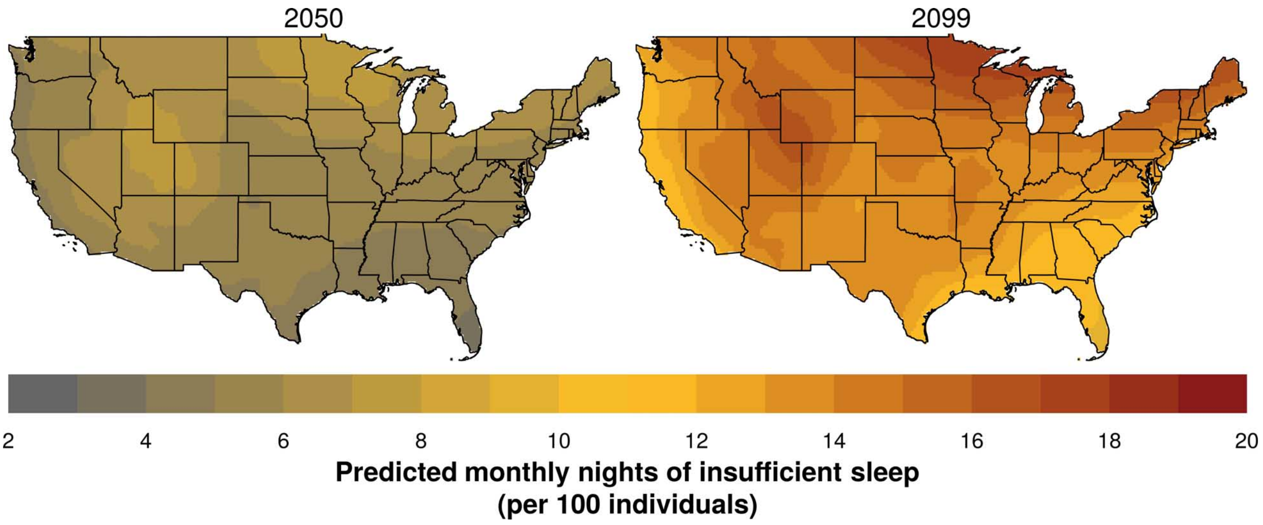

Fig. 4. Geographic dispersion of the predicted effects of climate change–induced nighttime warming on human sleep. This figure presents the 25-km × 25-km grid cell forecasts of the potential impact of nighttime warming on monthly nights of insufficient sleep per 100 individuals. Downscaled climatic model data are averaged across the 21 models in the ensemble and then coupled with our historical model parameter β to produce an estimated change in insufficient sleep in each geographic location for the periods of 2050 and 2099. Areas of the western and northern United States—where nighttime temperatures are projected to increase most acutely—may experience the largest future changes in sleep.

future downscaled climatic projections into our forecast (*29*). Figure 3B plots the estimation results. Each of the 219 cities in our analysis has a prediction for each of the 21 downscaled climate models, producing approximately 4600 estimates per period. On average, we project that climate change may cause approximately 6 additional nights of insufficient sleep per 100 individuals by 2050 and an excess of approximately 14 nights per 100 individuals by 2099 (see Fig. 3C).

In addition, the effects of climate change on nighttime temperatures—and thus the potential impacts of climate change on sleep—are likely to vary geographically across the United States. To investigate the spatial distribution of potential reductions in sufficient sleep due to climate change, we take the ensemble average of the 21 NEX downscaled climate models for each of the 2010, 2050, and 2099 forecasts. We then take the yearly average of nighttime temperature anomalies for each grid cell in the continental United States in each year. For the 2050 forecast, we assign to each grid cell the difference in average nighttime temperature anomaly between 2010 and 2050. For the 2099 forecast, we assign to each grid cell the difference in average anomalies between 2010 and 2099. As can be seen in Fig. 4—with effects scaled to be per 100 individuals—areas of the western and northern United States are likely to have the most significant changes in nighttime temperatures and, as a result, may see the greatest increase in climate change–induced nights of insufficient sleep.

DISCUSSION

Our analysis of historical data demonstrates a robust link between atypical nightly temperatures and insufficient sleep that is largest during the summer and among lower-income individuals and the elderly. Moreover, across both our city-level and geographic grid cell–level forecasts, we predict that every location in the United States may experience an increased incidence of insufficient sleep due to nighttime warming induced by future climate change.

These findings correspond to a growing literature on the close ties between temperature, climate, and human health and well-being (*35*). Recent studies have demonstrated the effects of temperature on mortality and morbidity (*46*–*50*) as well as on psychological states and propensity for crime and other forms of violence (*51*–*54*), although, to our knowledge, ours is the first study to examine the implications of climate change for human sleep.

There are several considerations important to the interpretation of the results of this study. First, although we have data on hundreds of thousands of individuals' reports of insufficient sleep, optimal data would also contain objective measurements of each individual's nightly sleep duration. Reports of insufficient sleep may be driven due to actual sleep loss, but they may also be driven by other factors such as excess fatigue due to warmer than normal temperatures.

This point raises a second consideration: Here, we focus on the average treatment effect of nighttime temperature anomalies on a measure of sleep sufficiency. Yet, it is likely that there are interactive effects between sleep and other physiological and psychological metrics. Future study of these other metrics will be important to help identify the causal mechanisms underpinning our results. Third, future attainment of sufficient sleep will be determined by factors in addition to nighttime temperatures—including use of technology, hours worked, stress levels, changes to the built environment (*55*), and many others—that may each trend differentially going forward. The potential effects of nighttime warming on sleep may be exacerbated or even reduced by these other sleep-related trends. Further studies are needed to clarify how increased nighttime temperatures may interact with these factors. Fourth, because respondents are geolocated to the city level, measurement error may exist between the nighttime temperatures observed at weather stations and the temperatures respondents actually experienced, possibly attenuating the size of our estimates (*56*). This, in turn, suggests that our results may represent a lower bound for the estimate of "business as usual" climate change on human sleep. Finally, our analysis is conducted on a randomly sampled, pooled cross section of respondents. An ideal source of data would track the same individuals over time to enable controlling for individual-specific characteristics.

Ultimately, if observed temperature-sleep relationships from the recent past persist, further climate change–induced nighttime warming may reduce the attainment of sufficient sleep, magnifying many of the physiological and psychological costs of sleep deprivation. These costs may be most acute for the poor and elderly. Although adaptations to changing nighttime temperature distributions may mitigate some or all of these sleep effects, positive feedback loops from the other potential social impacts of climate change—such as increased stress, acute trauma, and interpersonal conflict—could amplify them.

MATERIALS AND METHODS

We collected data for this project from the public domain. We used the Centers for Disease Control and Prevention BRFSS Selected Metropolitan/Micropolitan Area Risk Trends product for our measure of nights of insufficient sleep. We gathered daily meteorological data from the National Centers for Environmental Information GHCN-D product, the NCEP Reanalysis 2, and the PRISM Climate Group. In addition, we incorporated climate model data from the NEX-GDDP bias-corrected, statistically downscaled models.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/3/5/e1601555/DC1

table S1. Monthly nighttime temperature anomalies and monthly nights of insufficient sleep.
table S2. Varying time and location controls.
table S3. Regressions by season.
table S4. Regressions by income level.
table S5. Regressions by age.
table S6. Average nighttime temperature regressions.
table S7. Demographic controls.
table S8. Negative binomial regressions.
table S9. Monthly nighttime temperature anomalies and any nights of insufficient sleep (0/1).
table S10. Monthly nighttime temperature anomalies (PRISM) and monthly nights of insufficient sleep.
fig. S1. Permutation test.
fig. S2. Cities and stations.

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Acknowledgments: We thank the San Diego Supercomputer Center for their assistance and the Human Nature Group at University of California, San Diego, for their helpful comments. Climate scenarios used were from the NEX-GDDP data set, prepared by the Climate Analytics Group and NASA Ames Research Center using the NEX, and distributed by the NASA Center for Climate Simulation. **Funding:** This work was supported by the NSF (DGE0707423 and TG-SES130013 to N.O. and DGE1247398 to R.M.). S.C.M. acknowledges funding from the NIH/National Institute on Aging (R01AG046646), the Department of Defense (Office of Naval Research Young Investigator Award), and the NSF (BCS1439210). **Author contributions:** N.O. constructed and analyzed the historical data, produced the figures, conducted the forecast, and compiled the Supplementary Materials. N.O. and R.M. conceived of the research question. All authors drafted the manuscript and edited the Supplementary Materials. **Competing interests:** N.O. serves as an unpaid member of an advisory council for the Skoll Global Threats Fund. The other authors declare that they have no competing interests. **Data and materials availability:** All data needed to evaluate the conclusions in the paper are present in the paper and/or the Supplementary Materials. Additional data related to this paper may be requested from the authors. Replication data and materials can be accessed via Harvard's Dataverse (doi: 10.7910/DVN/MYCMKG).

Submitted 7 July 2016
Accepted 23 March 2017
Published 26 May 2017
10.1126/sciadv.1601555

Citation: N. Obradovich, R. Migliorini, S. C. Mednick, J. H. Fowler, Nighttime temperature and human sleep loss in a changing climate. *Sci. Adv.* **3**, e1601555 (2017).

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Nick Obradovich, Robyn Migliorini, Sara C. Mednick and James H. Fowler (May 26, 2017)
Sci Adv 2017, 3:.
doi: 10.1126/sciadv.1601555

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