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Supplementary Materials for

Nighttime temperature and human sleep loss in a changing climate

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Main Effect

table S1. Monthly nighttime temperature anomalies and monthly nights of insufficient sleep.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Night Temp. Anomaly	0.029***	0.028**	0.028**	0.028***	0.028**	0.028**	0.027**	0.028**
	(0.011)	(0.011)	(0.011)	(0.011)	(0.011)	(0.011)	(0.011)	(0.011)
Night Temp. Anomaly^2		0.005						
		(0.003)						
Avg. Temp. Range			-0.008	0.033	-0.014	-0.014	-0.021	-0.022
			(0.012)	(0.050)	(0.012)	(0.012)	(0.016)	(0.016)
Avg. Temp. Range^2				-0.002				
				(0.002)				
Prcp. Anomaly					-0.005**	-0.005**	-0.004*	-0.004*
					(0.002)	(0.002)	(0.002)	(0.002)
Prcp. Anomaly^2						0.00004		
						(0.0001)		
Avg. Humidity							-0.003	-0.003
							(0.004)	(0.004)
Avg. Cloudcover								-0.001
								(0.003)
Date FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
City:Season FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	766,761	766,761	766,761	766,761	766,761	766,761	766,761	766,761
R^2	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009
Adjusted R^2	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004
Residual Std. Error	9.944	9.944	9.944	9.944	9.944	9.944	9.944	9.944

Notes:
***Significant at the 1 percent level.
**Significant at the 5 percent level.
*Significant at the 10 percent level.
Standard errors are in parentheses and are clustered on city and date.

In this section we present the regression table associated with our main effect regression. Our unit of analysis is the individual-day. Our dependent variable throughout is an individuals' reported nights of insufficient sleep over the past month. Our main independent variable is the monthly average of nightly temperature deviations from the 1981-2010 daily normal nightly temperatures in the individuals' city. Our main specification is presented in model (8) of table S1. We examine the potential for a non-linear relationship between nightly temperature anomalies and insufficient sleep and find no evidence of quadratic effects. In subsequent models, we progressively add additional climatic control variables that might otherwise bias our estimates of the effect of nighttime temperature anomalies, with the effect size of nighttime temperature anomalies remaining mostly unchanged across these specifications.

Time and Location Controls

table S2. Varying time and location controls.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Night Temp. Anomaly	0.046***	0.027***	0.052***	0.053***	0.034***	0.021**	0.028**
	(0.013)	(0.009)	(0.016)	(0.013)	(0.009)	(0.010)	(0.011)
Avg. Temp. Range	-0.011	0.027**	-0.033	-0.012	0.023**	-0.032**	-0.022
	(0.021)	(0.011)	(0.023)	(0.021)	(0.011)	(0.013)	(0.016)
Prcp. Anomaly	-0.011***	-0.003	-0.010***	-0.011***	-0.003	-0.003	-0.004*
	(0.004)	(0.002)	(0.004)	(0.004)	(0.002)	(0.002)	(0.002)
Avg. Humidity	0.009	-0.004*	0.009	0.009*	-0.004*	-0.007***	-0.003
	(0.006)	(0.002)	(0.006)	(0.005)	(0.002)	(0.003)	(0.004)
Avg. Cloudcover	-0.014**	0.002	-0.016***	-0.016***	0.0002	0.002	-0.001
	(0.005)	(0.002)	(0.006)	(0.005)	(0.002)	(0.002)	(0.003)
Linear Time Trend				0.002**	0.002**		
				(0.001)	(0.001)		
Quadratic Time Trend				-0.00000**	-0.00000**		
				(0.00000)	(0.00000)		
Constant	7.814***			-3.279			
	(0.511)			(6.117)			
City FE	No	Yes	No	No	Yes	Yes	No
Date FE	No	No	Yes	No	No	Yes	Yes
City:Season FE	No	No	No	No	No	No	Yes
N	766,761	766,761	766,761	766,761	766,761	766,761	766,761
R^2	0.0002	0.004	0.005	0.0003	0.004	0.008	0.009
Adjusted R^2	0.0002	0.003	0.002	0.0003	0.003	0.004	0.004
Residual Std. Error	9.965	9.950	9.959	9.965	9.950	9.945	9.944

Notes: ***Significant at the 1 percent level.
**Significant at the 5 percent level.
*Significant at the 10 percent level.
Standard errors are in parentheses and are clustered on city and date.

Our main specification uses a pooled cross-section of data from the BRFSS and employs both time, location, and location-by-season factors to partial out the potentially confounding effects of time, location, and location specific seasonality on our estimated coefficient. However, our results are robust to the omission of these controls (in a purely cross-sectional model), controlling for only time or only location effects, to parametrically controlling for time trends, and to controlling for city-specific flexible seasonal trends (city-by-season fixed effects) in addition to city and time specific factors. Table S2 presents the results of these specifications. The coefficient on nightly temperature anomalies remains statistically significant throughout.

Season

table S3. Regressions by season.

	Spring	Summer	Fall	Winter
	(1)	(2)	(3)	(4)
Night Temp. Anomaly	0.022	0.073**	0.009	0.026
	(0.024)	(0.031)	(0.022)	(0.017)
Avg. Temp. Range	-0.017	0.031	-0.112***	0.052*
	(0.029)	(0.032)	(0.029)	(0.031)
Prcp. Anomaly	-0.001	-0.006	0.001	-0.008
	(0.004)	(0.005)	(0.005)	(0.006)
Avg. Humidity	-0.006	-0.005	-0.010	0.008
	(0.007)	(0.007)	(0.007)	(0.007)
Avg. Cloudcover	-0.002	0.004	-0.006	-0.0004
	(0.005)	(0.005)	(0.006)	(0.005)
City FE	Yes	Yes	Yes	Yes
Date FE	Yes	Yes	Yes	Yes
N	191,984	179,117	207,157	188,503
R^2	0.008	0.009	0.010	0.009
Adjusted R^2	0.004	0.004	0.005	0.004
Residual Std. Error	9.999	9.962	9.963	9.852

Notes: ***Significant at the 1 percent level.
**Significant at the 5 percent level.
*Significant at the 10 percent level.
Standard errors are in parentheses and are clustered on city and date.

In this section we present our regression tables associated with running our main model specification by season (we exclude city-by-season fixed effects from this specification due to multicollinearity). As can be seen in table S3 model (2), summer is associated with over twice the effect size of any other season.

Income

table S4. Regressions by income level.

	Low Income	High Income
	(1)	(2)
Night Temp. Anomaly	0.042***	0.012
	(0.016)	(0.017)
Avg. Temp. Range	-0.001	-0.040
	(0.023)	(0.026)
Prcp. Anomaly	-0.0004	-0.006
	(0.004)	(0.004)
Avg. Humidity	0.001	-0.005
	(0.005)	(0.006)
Avg. Cloudcover	-0.001	-0.003
	(0.004)	(0.004)
Date FE	Yes	Yes
City:Season FE	Yes	Yes
N	342,565	322,044
R^2	0.016	0.017
Adjusted R^2	0.005	0.006
Residual Std. Error	10.469	9.364

Notes: ***Significant at the 1 percent level.
**Significant at the 5 percent level.
*Significant at the 10 percent level.
Standard errors are in parentheses and are clustered on city and date.

In this section we present our regression tables associated with running our main model specification split by median income bracket ($50,000). As can be seen in table S4 model (1), the effect of average monthly nighttime temperature anomalies on insufficient sleep in the low income category is statistically significant and associated with over three times the effect size within the high income category.

Age

table S5. Regressions by age.

	Under 65	65 and Over
	(1)	(2)
Night Temp. Anomaly	0.025*	0.041**
	(0.013)	(0.020)
Avg. Temp. Range	-0.021	-0.009
	(0.018)	(0.025)
Prcp. Anomaly	-0.005*	-0.001
	(0.003)	(0.004)
Avg. Humidity	-0.004	-0.002
	(0.005)	(0.005)
Avg. Cloudcover	-0.001	0.001
	(0.004)	(0.004)
Date FE	Yes	Yes
City:Season FE	Yes	Yes
N	535,968	223,211
R^2	0.012	0.019
Adjusted R^2	0.005	0.004
Residual Std. Error	10.150	8.757

Notes: ***Significant at the 1 percent level.
**Significant at the 5 percent level.
*Significant at the 10 percent level.
Standard errors are in parentheses and are clustered on city and date.

In this section we present our regression tables associated with running our main model specification split by age bracket ('Under 65' and '65 and Over'). As can be seen in table S5 model (2), the effect of average monthly nighttime temperature anomalies on insufficient sleep in the older adult category is statistically significant and associated with almost twice the effect size observed within the younger adult category (which also returns a statistically significant effect).

Average Nighttime Temperatures

table S6. Average nighttime temperature regressions.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Avg. Night Temp.	0.005	0.009***	-0.006	0.006	0.011***	0.014***	0.021**
	(0.004)	(0.002)	(0.008)	(0.004)	(0.002)	(0.005)	(0.009)
Avg. Temp. Range	-0.012	0.009	-0.038*	-0.013	0.001	-0.037***	-0.026
	(0.020)	(0.012)	(0.021)	(0.021)	(0.012)	(0.013)	(0.016)
Sumtotal Prc.	0.015**	0.0001	0.015**	0.015**	0.0001	-0.002	-0.004*
	(0.006)	(0.002)	(0.006)	(0.006)	(0.002)	(0.002)	(0.002)
Avg. Humidity	0.007	-0.007**	0.006	0.008	-0.007**	-0.008***	-0.003
	(0.005)	(0.003)	(0.005)	(0.005)	(0.003)	(0.003)	(0.004)
Avg. Cloudcover	-0.018***	0.002	-0.018***	-0.020***	-0.0001	0.001	-0.001
	(0.006)	(0.002)	(0.006)	(0.005)	(0.002)	(0.002)	(0.003)
Linear Time Trend				0.002**	0.002**		
				(0.001)	(0.001)		
Quadratic Time Trend				-0.00000**	-0.00000**		
				(0.00000)	(0.00000)		
Constant	8.009***			-1.479			
	(0.472)			(5.413)			
City FE	No	Yes	No	No	Yes	Yes	No
Date FE	No	No	Yes	No	No	Yes	Yes
City:Season FE	No	No	No	No	No	No	Yes
N	766,761	766,761	766,761	766,761	766,761	766,761	766,761
R^2	0.0003	0.004	0.005	0.0004	0.004	0.008	0.009
Adjusted R^2	0.0003	0.003	0.002	0.0004	0.003	0.004	0.004
Residual Std. Error	9.965	9.950	9.959	9.965	9.949	9.945	9.944

Notes: ***Significant at the 1 percent level.
**Significant at the 5 percent level.
*Significant at the 10 percent level.
Standard errors are in parentheses and are clustered on city and date.

Our main specification uses deviations from average temperature as its main independent variable. However, we might also be interested in seeing whether levels of nighttime temperatures also impact sleep in a similar way. To test this, we examine the thirty day average of nighttime temperature levels on reported insufficient sleep.

The effect of a one degree increase in the level of temperature is similar in magnitude to the effect of a one degree increase in temperature from its normal value. These results are robust to the same time and location controls employed in table S2 and can be seen in table S6. The coefficient on average nightly temperature is statistically significant in model (7), which mirrors our specification from Equation 1 in the main text. As the levels of nighttime temperature increase, sleep tends to worsen on average.

Demographic Controls

table S7. Demographic controls.

Night Temp. Anomaly	0.027**
	(0.012)
Avg. Temp. Range	-0.012
	(0.016)
Prcp. Anomaly	-0.003
	(0.003)
Avg. Humidity	-0.002
	(0.004)
Avg. Cloudcover	-0.002
	(0.003)
Age	-0.145***
	(0.002)
Hispanic	1.646***
	(0.129)
Education	-0.168***
	(0.022)
Income	-0.357***
	(0.016)
Employment	0.035***
	(0.011)
Female	1.092***
	(0.029)
Date FE	Yes
City:Season FE	Yes
N	657,161
R^2	0.063
Adjusted R^2	0.058
Residual Std. Error	9.676

Notes: ***Significant at the 1 percent level.
**Significant at the 5 percent level.
*Significant at the 10 percent level.
Standard errors are in parentheses and are clustered on city and date.

Some might desire that we control for common demographic covariates. Unfortunately, as these demographic characteristics may also be impacted by the climatic variables within a locality (for example, if a particular demographic sorts into living in less extreme environments), including these variables has the potential to bias our coefficient of interest on nighttime temperature anomalies (making the variables ‘bad controls’). As a result we exclude them from our specification in Equation 1 in the main text. However, our coefficient estimates remain mostly unchanged by the inclusion of common demographic controls like age, ethnicity, education, income, employment status, and sex. Table S7 presents the results of this specification. The coefficient on nightly temperature anomalies remains statistically significant and of similar magnitude. Of note, our sample size in this regression decreases as not every individual answered demographic covariate questions.

Negative Binomial

table S8. Negative binomial regressions.

	(1)	(2)	(3)	(4)	(5)
Night Temp. Anomaly	0.006***	0.004***	0.007***	0.004***	0.003**
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Avg. Temp. Range	-0.001	0.003**	-0.002*	0.003**	-0.004**
	(0.001)	(0.001)	(0.001)	(0.001)	(0.002)
Prcp. Anomaly	-0.001***	-0.0003	-0.001***	-0.0004	-0.0004
	(0.0003)	(0.0004)	(0.0003)	(0.0004)	(0.0004)
Avg. Humidity	0.001***	-0.001	0.001***	-0.001	-0.001**
	(0.0003)	(0.0004)	(0.0003)	(0.0004)	(0.0004)
Avg. Cloudcover	-0.002***	0.0003	-0.002***	0.00003	0.0002
	(0.0002)	(0.0003)	(0.0003)	(0.0003)	(0.0003)
Linear Time Trend			0.0002***	0.0002***	
			(0.0001)	(0.0001)	
Quadratic Time Trend			-0.000***	-0.000***	
			(0.000)	(0.000)	
Constant	2.056***	2.071***	0.578	0.611	2.192***
	(0.025)	(0.045)	(0.499)	(0.525)	(0.059)
City FE	No	Yes	No	Yes	Yes
Year-Month FE	No	No	No	No	Yes
Day-of-Week FE	No	No	No	No	Yes
N	766,761	766,761	766,761	766,761	766,761
Log Likelihood	-2,245,762.000	-2,244,980.000	-2,245,741.000	-2,244,967.000	-2,244,860.000
theta	0.381***	0.382***	0.381***	0.382***	0.383***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Akaike Inf. Crit.	4,491,536.000	4,490,408.000	4,491,498.000	4,490,386.000	4,490,377.000

Notes: ***Significant at the 1 percent level.
**Significant at the 5 percent level.
*Significant at the 10 percent level.
Standard errors are in parentheses.

In the main text we employ ordinary least squares regression for its ease of interpretation. This method takes as an assumption that our dependent variable is continuous. However, our dependent variable is ultimately a count from zero to thirty – not fully continuous. Our results are robust to using an appropriate count-data model – the negative binomial – with similar time and location controls. We are unable to invert the full matrix of both city and calendar day specific indicator variables via **R**'s negative binomial (*glm.nb()*) function (the *felm()* function of the *lfe* package does this efficiently in the case of OLS) so we estimate the model with day of week and year-month specific indicators as well as a combination of parametric time trends to control for time fixed effects. Table S8 presents the results of these specifications. The coefficient on nightly temperature anomalies remains statistically significant throughout.

Linear Probability Model

table S9. Monthly nighttime temperature anomalies and any nights of insufficient sleep (0/1).

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Night Temp. Anomaly	0.002***	0.002***	0.002***	0.002***	0.002***	0.002***	0.002***	0.002***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Night Temp. Anomaly^2		0.0002						
		(0.0002)						
Avg. Temp. Range			-0.001	-0.001	-0.001	-0.001	-0.001	-0.0005
			(0.001)	(0.003)	(0.001)	(0.001)	(0.001)	(0.001)
Avg. Temp. Range^2				0.00002				
				(0.0001)				
Prcp. Anomaly					-0.0002	-0.0002	-0.0002	-0.0002
					(0.0001)	(0.0001)	(0.0001)	(0.0001)
Prcp. Anomaly^2						0.00001		
						(0.00000)		
Avg. Humidity							-0.00003	-0.0002
							(0.0002)	(0.0002)
Avg. Cloudcover								0.0003**
								(0.0001)
Date FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
City:Season FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	766,761	766,761	766,761	766,761	766,761	766,761	766,761	766,761
R^2	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011
Adjusted R^2	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006
Residual Std. Error	0.476	0.476	0.476	0.476	0.476	0.476	0.476	0.476

Notes: ***Significant at the 1 percent level.
**Significant at the 5 percent level.
*Significant at the 10 percent level.
Standard errors are in parentheses and are clustered on city and date.

As another robustness check, we convert our main dependent variable into a binary measure of whether or not a respondent reported any nights of insufficient sleep over the past month. If a respondent reported any nights of sleep, we code the variable as one and code it as zero otherwise. Table S9 reproduces table S1 utilizing this binary dependent variable. In these linear probability models, the coefficients on nighttime temperature anomalies can be interpreted as the marginal effect of a one degree Celsius anomalous increase in nighttime temperature on the individual probability of reporting any nights of insufficient sleep. As can be seen in table S9, nighttime temperature anomalies are consistent in both sign, magnitude, and significance across the models.

Permutation Test

As a further robustness check, we report the results of a permutation test where we run a batch of regressions on randomly re-assigned nighttime temperature anomalies and compare the coefficients on these placebo nighttime temperature anomalies to the true coefficient we estimate from Equation 1 in the main text. Specifically, we randomly sample and assign (with replacement) nighttime temperature anomalies from our data and then conduct the regression in Equation 1 on these randomly sampled temperature anomalies. We repeat this sampling and regression 10,000 times to generate a distribution of placebo coefficients. As can be seen in fig. S1, the true coefficient value as estimated via Equation 1 in the main text falls substantially outside the distribution of coefficients estimated on the randomly shuffled nighttime temperature anomalies.

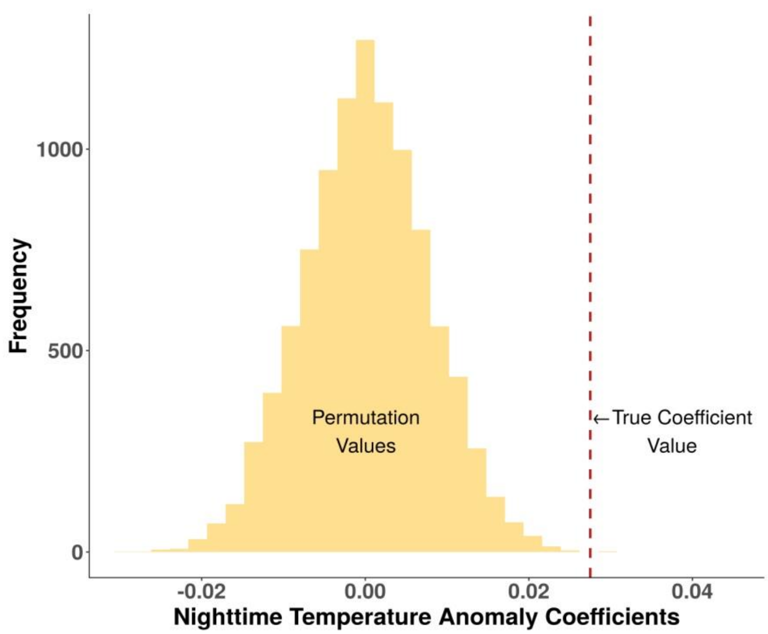

fig. S1. Permutation test. This figure plots permutation test coefficients alongside the true coefficient value on nighttime temperature anomalies from Equation 1 in the main text.

PRISM Data

table S10. Monthly nighttime temperature anomalies (PRISM) and monthly nights of insufficient sleep.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Night Temp. Anomaly	0.027**	0.026**	0.025**	0.024**	0.026**	0.025**	0.024**	0.024**
	(0.012)	(0.012)	(0.011)	(0.011)	(0.012)	(0.012)	(0.011)	(0.012)
Night Temp. Anomaly^2		0.003						
		(0.003)						
Avg. Temp. Range			-0.018	-0.026	-0.026**	-0.027**	-0.040**	-0.040**
			(0.012)	(0.045)	(0.013)	(0.013)	(0.016)	(0.017)
Avg. Temp. Range^2				0.0003				
				(0.002)				
Prcp. Anomaly					-0.001**	-0.001	-0.0005*	-0.0005*
					(0.0003)	(0.001)	(0.0003)	(0.0003)
Prcp. Anomaly^2						0.00000		
						(0.00000)		
Avg. Humidity							-0.005	-0.005
							(0.004)	(0.004)
Avg. Cloudcover								0.0002
								(0.003)
Date FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
City:Season FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	734,436	734,436	734,436	734,436	734,436	734,436	734,436	734,436
R^2	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009
Adjusted R^2	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004
Residual Std. Error	9.968	9.968	9.968	9.968	9.968	9.968	9.968	9.968

Notes: ***Significant at the 1 percent level.
**Significant at the 5 percent level.
*Significant at the 10 percent level.
Standard errors are in parentheses and are clustered on city and date.

In order to ensure that our main results are robust to use of both station-based and gridded meteorological data, here we reproduce our main effects (table S1) using gridded daily meteorological data obtained from the PRISM Climate Group. As can be seen in table S10, our main results on nighttime temperature anomalies persist with the use of these alternative data. Of note, the PRISM project is only for the continental United States, and so this analysis excludes Alaska and Hawaii, somewhat reducing the power of our regressions.

Cities and Stations

fig. S2. Cities and stations. Red points indicate the locations of cities of respondents included in analysis, excluding those from Alaska and Hawaii. City point size increases by the log of number of respondents in each city. Yellow points indicate the location of weather station used in the analysis.

In this section we present the locations of the cities included in our analysis as well as the weather station locations mapped to their nearest cities. As can be seen in fig. S2, where city points are sized by the log of the number of respondents in the analysis, weather station locations map closely to city centroids, with the median distance from city centroid to station is 7 kilometers.