

Temperature exposure and sleep duration: Evidence from time use surveys

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Introduction

- ▶ Sleep is essential for humans and other animals
- ▶ We spend about one-third of our life sleeping
- ▶ Insufficient sleep and sleep disturbances are associated with negative consequences
 - ▶ higher mortality risk, hypertension, cardiovascular diseases
 - ▶ anxiety, greater interpersonal conflict, social withdrawal
 - ▶ worse cognitive performance
- ▶ Given the threat of climate change, the question of how temperature affects human sleep naturally arises

Previous studies on the temperature-sleep relationship

- ▶ Mainly of laboratory experiments
 - ▶ small sample sizes (often <10)
 - ▶ special experimental situations (e.g., electric blanket, sleeping naked at different room temperatures)
- ▶ Large-scale studies in real-world settings are rare
 - ▶ notable exceptions: Obradovich et al. (2017), Minor et al. (2022), Mullins and White (2019)
- ▶ Limitations and unanswered questions remain in terms of
 - ▶ measurement of sleep
 - ▶ data collection strategy
 - ▶ understanding the potential impact of climate change

The present study

- ▶ Estimate the effect of ambient temperature on sleep duration and project the impact of climate change
- ▶ Large number of time-use diaries from a thirty-five-year period
- ▶ Address prior concerns regarding measurement and generalizability
- ▶ Provide an opportunity for an in-depth examination of heterogeneities and changes over time

Data

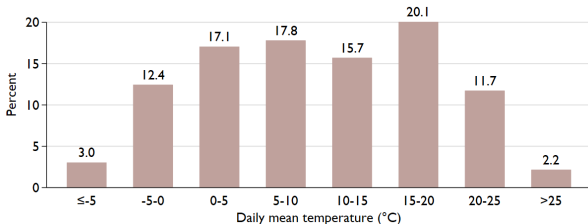
1. Hungarian Time Use Survey - sleep
2. European Climate Assessment and Dataset project - weather
3. NASA Earth Exchange Global Daily Downscaled Projections - future climate

Time use surveys

- ▶ Hungarian Time Use Survey (HTUS) administered by the Hungarian Central Statistical Office
 - ▶ 1976/1977, 1986/1987, 1993, 1999/2000, and 2009/2010
- ▶ Face-to-face interview
- ▶ Activities for the previous day (24 hours)
- ▶ The analysis sample is restricted to adults (120,601 diaries of 46,446 individuals)
 - ▶ in three waves each respondent completed four diaries (one per season)
- ▶ Main dependent variable: sleep duration (measured in minutes)
 - ▶ includes all sleep and nap periods
 - ▶ mean = 513 minutes (\approx 520 minutes in ATUS)

Historical weather observations

- ▶ European Climate Assessment and Dataset project (E-OBS 27.0e dataset)
- ▶ Daily temperatures and other weather data for Europe with a spacing of $0.1^\circ \times 0.1^\circ$ in regular latitude/longitude coordinates
- ▶ Gridded data → aggregated to the county (NUTS 3) level
 - ▶ county-by-day level dataset
 - ▶ mean temperature, precipitation, relative humidity
- ▶ Temperature categories based on daily mean temperature



Temperature change in the 21st century

- ▶ NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP-CMIP6)
- ▶ Daily temperature projections (2015-2100) and retrospectively simulated historical data (1950-2014)
 - ▶ Spatial resolution: $0.25^\circ \times 0.25^\circ$
- ▶ Twenty-four climate models
- ▶ Four climate scenarios: SSP1-2.6 (optimistic), SSP2-4.5, SSP3-7.0, and SSP5-8.5 (worst-case)
- ▶ Within-model changes in the annual temperature distribution for each decade between 2020 and 2099
 - ▶ $\Delta T_{olg}^j = T_{olg}^j - \hat{T}_{ol}^j$
 - ▶ o stands for the SSP scenario, l denotes the climate model, and g denotes the decade
 - ▶ T : annual number of days when the daily mean temperature falls into temperature category j
 - ▶ baseline period: 1990-2014 (\hat{T})

The effect of daily mean temperature

$$S_{icymd} = \sum_j \beta^j T_{cymd}^j + \sum_k \gamma^k P_{cymd}^k + \sum_l \pi^l H_{cymd}^l + \delta X_{icymd} + \rho_{cym} + \varepsilon_{icymd}$$

- ▶ S is the sleep duration of individual i living in county c , in year y , month m , and day d
- ▶ T : temperature (ref.cat.: 5–10°C)
- ▶ P : precipitation (0, 0-3, 3-5, 5-10, >10 mm)
- ▶ H : relative humidity (≤ 50 , 50-60, 60-70, 70-80, >80%).
- ▶ X : characteristics of the respondent and the interview day
 - ▶ gender, age category, education, labor market status, household size, day-of-week, and an indicator of public holidays
- ▶ County-by-year-by-month fixed effects (ρ_{cym})
- ▶ The standard errors are clustered at the county and individual levels (two-way clustering)

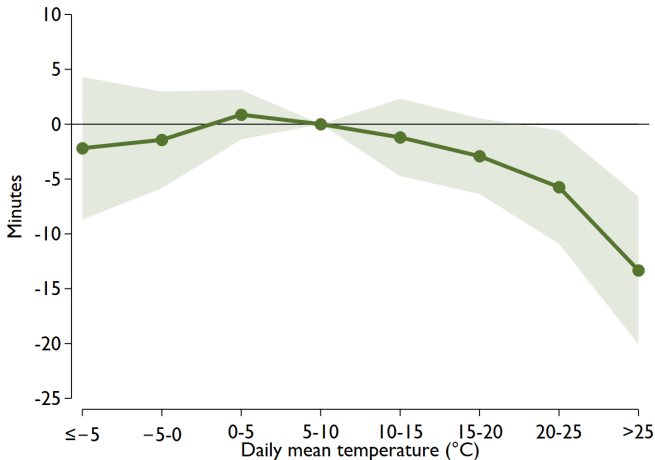
The effect of climate change

$$\Delta S_{bolg} = \sum_j \beta_b^j \Delta T_{olg}^j$$

- ▶ b - the bootstrap sample (1-200), o - SSP scenario, l - climate model, and g - decade
- ▶ Uncertainty in the relationship between temperatures and sleep duration is captured by bootstrapping β (200 times, sampling with replacement)
- ▶ Each ΔS is a projection for the change in sleep duration (per person per year) due to changes in the temperature distribution
- ▶ For each SSP scenario-decade pair, 4,800 projections are considered (24 climate models \times 200 estimates of the temperature-sleep relationship, ΔS_{og})

Heat reduces sleep duration

- ▶ The effect of a $>25^{\circ}\text{C}$ day is -13.3 minutes (-2.6%, compared to average daily sleep time)



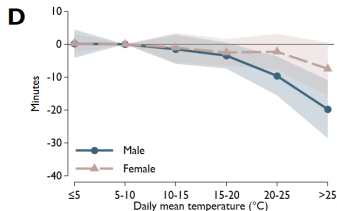
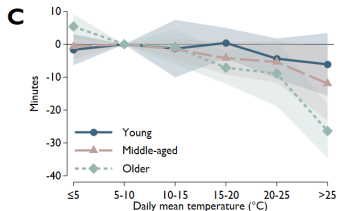
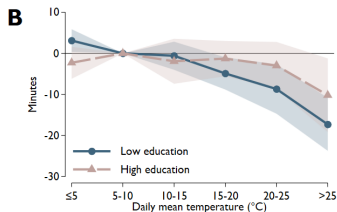
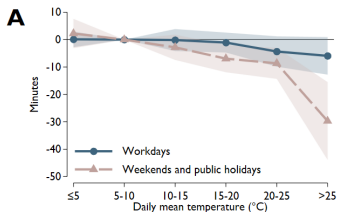
Robustness

- ▶ Restricted cubic spline regression or using narrower (2 °C-wide) temperature categories [▶ Figure](#)
- ▶ Falsification test with future temperatures [▶ Figure](#)
- ▶ Maximum or minimum temperature [▶ Figure](#)
- ▶ Individual fixed effects [▶ Figure](#)
- ▶ Different fixed effects, exclusion of control variables, alternative methods for clustering the standard errors [▶ Table](#)
- ▶ Checking whether ambient temperature affects participation in the time use survey [▶ Table](#)
- ▶ Alternative outcome variables: the total sleep time is <6 hours, 6-8 hours, 8-9 hours, or ≥ 9 hours [▶ Figure](#)
- ▶ Including sunset/sunrise times or daylength [▶ Table](#)

Heterogeneity

- ▶ The heat-induced sleep loss is larger on weekends/public holidays, for older individuals, for individuals with low education, and for men

▶ Tables

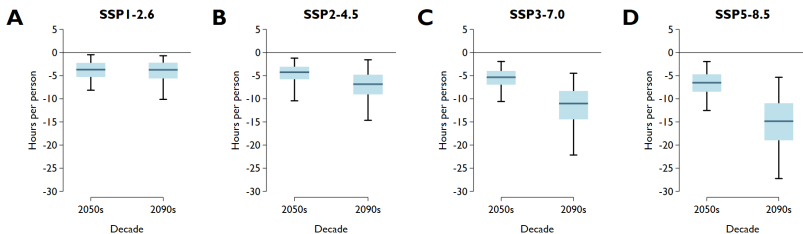


Further results

- ▶ The effect of a heatwave day is stronger than that of an “ordinary” hot day [▶ Table](#)
- ▶ Night sleep vs. daytime sleep [▶ Figure](#)
- ▶ Waking up and going to bed [▶ Figure](#)
- ▶ Previous days’ temperatures do not influence sleep duration [▶ Figure](#)
- ▶ The effect of heat has not changed over the thirty-five years of the sample [▶ Figure](#)

Climate change reduces sleep duration

- ▶ Median projections, 2090s: -3.7 hours, -6.8 hours, -11.0 hours, and -14.8 hours (per person per year)



The box plots show the medians, the interquartile ranges, and the middle 95% of the projections.

- ▶ Heterogeneous impacts: older [▶ Figure](#) and less educated people [▶ Figure](#) suffer more sleep loss

Discussion

- ▶ The negative effects of temperature and climate change on heat can lead to further consequences
- ▶ Previous studies found that heat...
 - ▶ increases workplace injuries, aggression/crime
 - ▶ and decreases cognitive performance/learning, health
- ▶ Sleep may be one of the channels through which heat "works"
- ▶ The impact of Daylight Saving Time
 - ▶ at the spring transition: a decrease of 40-60 minutes of sleep
 - ▶ → increases in fatal car accidents, workplace injuries, and heart attacks
- ▶ Variation in the timing of natural light across time zones
 - ▶ a regular loss of 8-30 minutes of sleep per day
 - ▶ → negative effects on test scores, cognitive skills, depression symptoms, cardiovascular diseases, and income

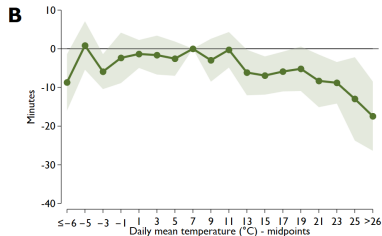
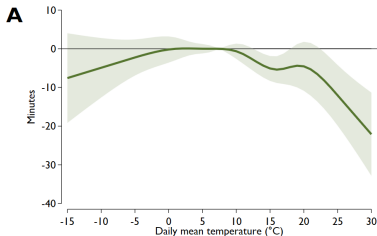
Conclusions

- ▶ Ambient temperature affects sleep duration
- ▶ As daily mean temperatures rise above 10°C, sleep duration starts to decrease
- ▶ The effect of a hot (>25°C) day is -13.3 minutes (compare to a 5–10°C day)
- ▶ For the Hungarian adult population, the total sleep loss on a >25°C day is 1 million hours, compared to a 20–25°C day (!)
- ▶ The effects are especially large on weekends and public holidays, for low educated and older individuals, and for males
- ▶ The warming climate is likely to decrease sleep duration during the 21st century
 - ▶ heterogeneous impacts need to be considered



Appendix

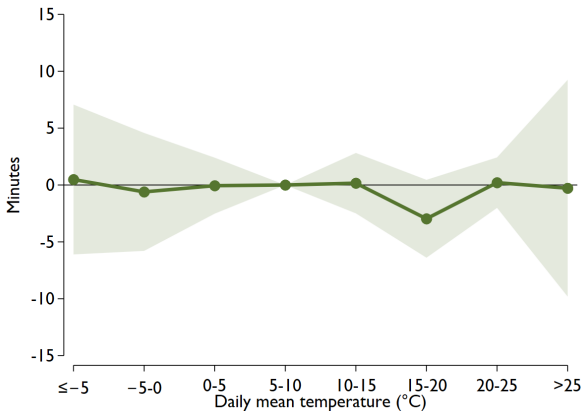
Similar patterns with spline and narrower temperature categories



(A) The estimates come from restricted cubic spline functions with six knots. The reference temperatures are 7.5°C. (B) 2°C-wide temperature bins, the lowest category is ≤-6°C, and the highest category is >26°C. The reference temperature is 6-8°C.

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Falsification test with future temperatures



Estimates based on temperature values measured one year after the completion of the time use diary.

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Descriptive statistics

Variable	Mean	SD	Min	Max	N
Sleep durations (minutes)	513.18	96.78	210	850	120,601
Wake-up time ^a	393.36	72.82	240	650	94,601
Time of going to bed ^a	1318.38	52.50	1140	1440	92,183
Daily mean temperature (°C)					
≤-5	0.030	0.171	0	1	120,601
-5 to 0	0.124	0.330	0	1	120,601
0 to 5	0.171	0.376	0	1	120,601
5 to 10	0.178	0.382	0	1	120,601
10 to 15	0.157	0.364	0	1	120,601
15 to 20	0.201	0.401	0	1	120,601
20 to 25	0.117	0.322	0	1	120,601
>25	0.022	0.146	0	1	120,601

Notes: Weighted figures. ^a Measured in minutes starting from 0:00. Bedtime can be between 19:00 and 23:59 and wake-up time can be between 4:00 and 10:59.

The effect of a heatwave day is stronger

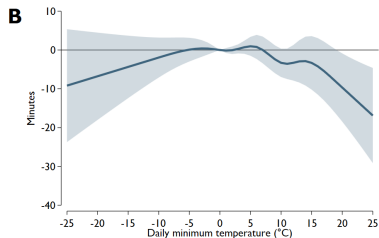
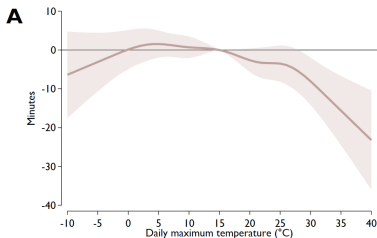
- ▶ heatwave = a period of several consecutive days when the daily mean temperature exceeds 25°C

Table 3. The effects of heatwave days

Daily mean temperature (°C)	(1) Heatwave: at least 3 days	(2) Heatwave: at least 5 days
≤5	0.2 (1.2)	0.2 (1.2)
5 to 10	ref. cat.	ref. cat.
10 to 15	-1.3 (1.7)	-1.3 (1.7)
15 to 20	-3.0* (1.7)	-3.0* (1.6)
20 to 25	-5.8** (2.5)	-5.9** (2.5)
>25 (non-heatwave day)	-12.5*** (4.4)	-11.4*** (3.6)
>25 (heatwave day)	-14.8*** (3.4)	-24.7*** (5.3)
R-squared	0.17	0.17
N of diaries	120,601	120,601
p-value (non-heatwave day vs. heatwave day)	0.65	0.03

Notes: The models have controls for precipitation, humidity, the characteristics of the respondent and the interview day (gender, age, education, labor market status, household size, day-of-week, public holiday), and county-by-year-by-month fixed effects. Standard errors clustered at the county and individual levels are in parentheses. * p < 0.10, ** p < 0.05, *** p < 0.01

Daily maximum and minimum temperatures



The estimates come from restricted cubic spline functions with seven knots. The reference temperatures are 15°C (A) and 0°C (B).

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Sensitivity tests

Table A3. Sensitivity tests

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Daily mean temperature (°C)	Baseline	Excl. controls	Excl. precipitation and humidity	C-Y, C-M FE	C, Y, M FE + time trend	C-Y, C-M FE + time trend	County + Y-M clustering
≤-5	-2.2 (3.1)	-3.7 (3.2)	-2.6 (3.1)	-2.9 (2.8)	-2.2 (3.0)	-2.1 (2.8)	-2.2 (4.3)
-5 to 0	-1.4 (2.1)	-3.4* (1.9)	-1.5 (2.2)	-2.4 (1.9)	-2.2 (2.0)	-1.4 (2.1)	-1.4 (2.4)
0 to 5	0.9 (1.1)	0.5 (1.3)	1.0 (1.1)	0.4 (0.9)	0.4 (1.0)	0.9 (1.1)	0.9 (1.4)
5 to 10	ref. cat.	ref. cat.	ref. cat.	ref. cat.	ref. cat.	ref. cat.	ref. cat.
10 to 15	-1.2 (1.7)	-1.3 (1.8)	-1.7 (1.6)	-1.5 (1.8)	-1.7 (1.9)	-0.8 (1.8)	-1.2 (1.6)
15 to 20	-2.9* (1.6)	-4.9*** (1.7)	-4.4*** (1.4)	-2.9 (1.7)	-2.9 (1.7)	-2.6 (1.7)	-2.9* (1.4)
20 to 25	-5.7** (2.5)	-8.7*** (2.3)	-7.7*** (2.1)	-5.6** (2.3)	-5.7** (2.3)	-5.2** (2.4)	-5.7** (2.3)
>25	-13.3*** (3.2)	-11.5*** (3.7)	-16.0*** (2.8)	-12.8*** (3.0)	-12.5*** (3.3)	-13.4*** (3.2)	-13.3*** (2.9)
Fixed effects	C-Y-M	C-Y-M	C-Y-M	C-Y, C-M	C, Y, M	C-Y, C-M	C-Y-M
Time trend	No	No	No	No	C-spec. quadratic	C-M-spec. quadratic	No
Controls	Yes	No	Yes	Yes	Yes	Yes	Yes
Precipitation and humidity	Yes	Yes	No	Yes	Yes	Yes	Yes
SE clustering	County + individual	County + individual	County + individual	County + individual	County + individual	County + individual	County + Y-M
Weighted	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R-squared	0.17	0.03	0.17	0.16	0.16	0.17	0.17
N of diaries	120,601	120,601	120,601	120,601	120,601	120,601	120,601

Notes: Controls: gender, age, education, labor market status, household size, day-of-week, public holiday. Standard errors are in parentheses.

* p < 0.10, ** p < 0.05, *** p < 0.01

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Temperature and respondent characteristics

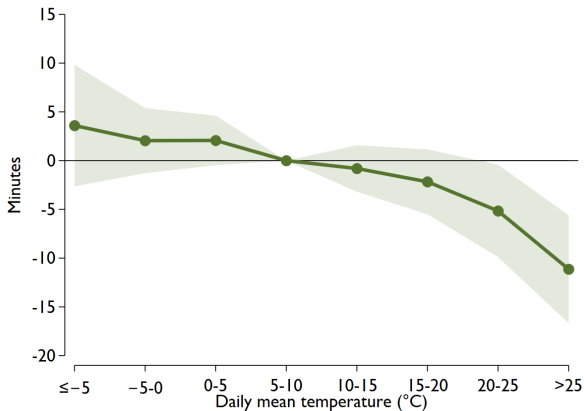
Table A5. Temperature and respondent characteristics

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Daily mean temperature (°C)	Female	High education	Young	Middle-aged	Older	Employed	Retired	Other	Large household size
≤-5	0.015 (0.015)	-0.000 (0.015)	-0.018 (0.011)	0.001 (0.013)	0.017 (0.013)	0.000 (0.019)	0.017 (0.014)	-0.017 (0.012)	-0.012 (0.013)
-5 to 0	0.012 (0.015)	0.008 (0.012)	0.012 (0.010)	-0.005 (0.012)	-0.007 (0.010)	0.006 (0.015)	-0.008 (0.011)	0.003 (0.008)	-0.002 (0.008)
0 to 5	-0.001 (0.008)	-0.002 (0.011)	-0.000 (0.012)	0.010 (0.011)	-0.010 (0.007)	0.012 (0.010)	-0.008 (0.006)	-0.004 (0.008)	0.002 (0.005)
5 to 10	ref. cat.	ref. cat.	ref. cat.	ref. cat.	ref. cat.	ref. cat.	ref. cat.	ref. cat.	ref. cat.
10 to 15	0.003 (0.007)	-0.009* (0.005)	0.005 (0.009)	0.008 (0.011)	-0.012* (0.007)	0.004 (0.010)	-0.018*** (0.006)	0.014** (0.007)	0.014** (0.006)
15 to 20	0.015** (0.006)	0.002 (0.008)	0.001 (0.012)	0.006 (0.010)	-0.007 (0.008)	0.010 (0.011)	-0.014** (0.007)	0.005 (0.011)	0.008 (0.008)
20 to 25	0.008 (0.008)	0.005 (0.010)	0.004 (0.012)	-0.010 (0.012)	0.005 (0.008)	0.003 (0.011)	-0.007 (0.008)	0.004 (0.009)	0.008 (0.008)
>25	-0.002 (0.014)	-0.009 (0.014)	-0.014 (0.011)	0.003 (0.015)	0.011 (0.012)	-0.005 (0.016)	0.002 (0.016)	0.004 (0.013)	0.003 (0.012)
R-squared	0.01	0.17	0.02	0.02	0.03	0.06	0.04	0.03	0.04
N of diaries	120,601	120,601	120,601	120,601	120,601	120,601	120,601	120,601	118,380

Notes: The dependent variables are indicated in the titles of the columns. Precipitation, humidity, and county-by-year-by-month fixed effects are included. Standard errors clustered at the county and individual levels are in parentheses. * p < 0.10, ** p < 0.05, *** p < 0.01

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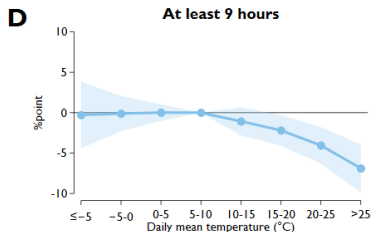
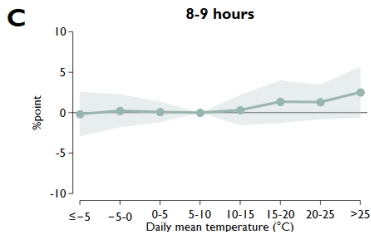
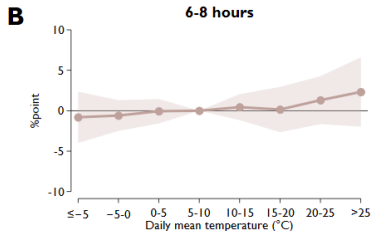
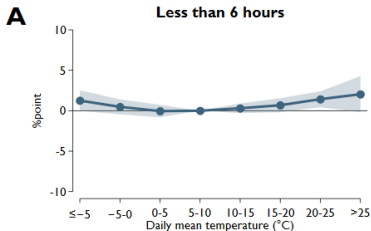
Estimates including individual fixed effects



The wave of 1993 and 2009/2010 are excluded, as only one diary was completed by each respondent.

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Binary outcomes indicating different sleep durations



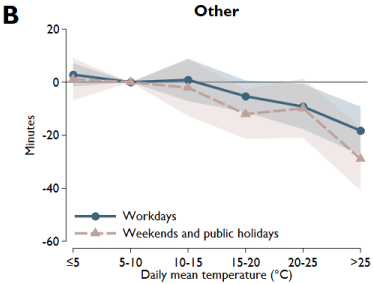
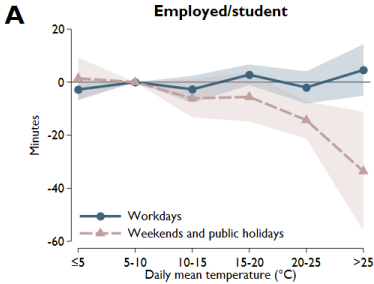
Controlling for sunset time, sunrise time, and daylength

Table A4. Controlling for sunset time, sunrise time, and daylength

Daily mean temperature (°C)	(1)	(2)	(3)
≤-5	-3.2 (3.2)	-5.1 (3.3)	-4.4 (3.3)
-5 to 0	-2.8 (2.3)	-3.4 (2.4)	-3.3 (2.4)
0 to 5	0.4 (1.1)	0.1 (1.2)	0.1 (1.1)
5 to 10	ref. cat.	ref. cat.	ref. cat.
10 to 15	-0.4 (1.7)	-0.8 (1.8)	-0.7 (1.8)
15 to 20	-1.9 (1.6)	-2.6 (1.6)	-2.4 (1.6)
20 to 25	-4.8* (2.4)	-5.3** (2.4)	-5.2** (2.4)
>25	-12.4*** (3.4)	-12.8*** (3.5)	-12.8*** (3.5)
Sunset time	Yes	No	No
Sunrise time	No	Yes	No
Daylength	No	No	Yes
R-squared	0.17	0.17	0.17
N of diaries	120,601	120,601	120,601

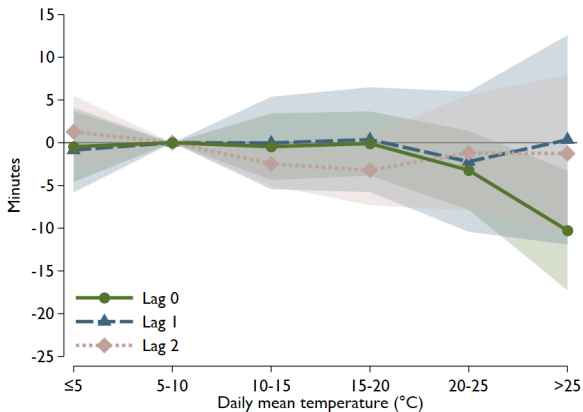
Notes: Sunset time, sunrise time, and daylength are continuous variables. They are measured at the county-level and included in the models as cubic polynomials. The models have controls for precipitation, humidity, the characteristics of the respondent and the interview day (gender, age, education, labor market status, household size, day-of-week, public holiday), and county-by-year-by-month fixed effects. Standard errors clustered at the county and individual levels are in parentheses. * p < 0.10, ** p < 0.05, *** p < 0.01

Temperature effects on workdays and holidays: employed/student vs. other



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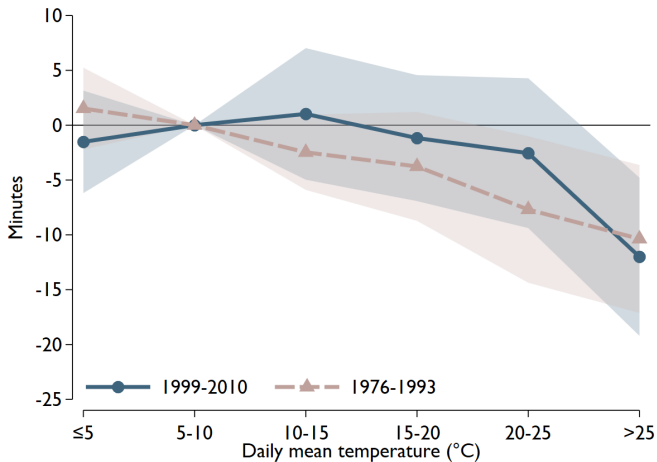
Temporal displacement



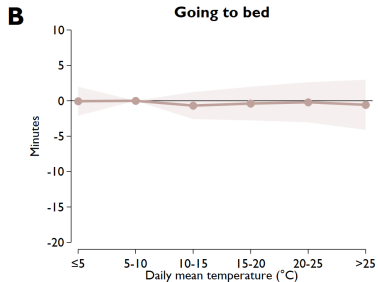
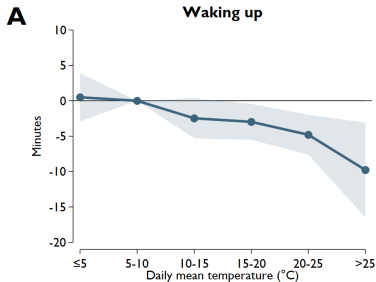
Lag 0 shows the contemporaneous effects, whereas lag 1 and lag 2 the effects of temperatures of the two previous days.

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The effect of temperature on sleep duration over time

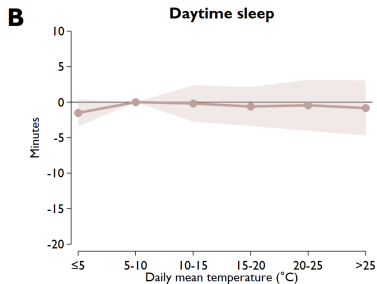
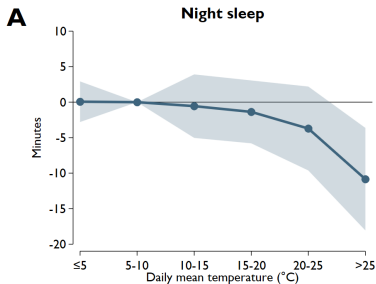


Waking up and going to bed

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Night and daytime sleep

- ▶ Night sleep: 20:00-7:59 ($\approx 96\%$ of total sleep)
- ▶ Daytime sleep: 8:00-19:59 ($\approx 4\%$ of total sleep)



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The effects of temperatures on workdays and non-workdays

Table A6. The effects of temperatures on workdays and non-workdays

	Workday	Weekend and public holidays	p
Daily mean temperature (°C)	(1)	(2)	(1) vs. (2)
≤5	0.1 (1.4)	2.2 (2.6)	0.47
5 to 10	ref. cat.	ref. cat.	
10 to 15	-0.2 (1.9)	-2.8 (2.2)	0.29
15 to 20	-1.1 (1.7)	-6.9*** (2.4)	0.01
20 to 25	-4.3 (2.6)	-8.7*** (2.7)	0.07
>25	-5.9* (3.3)	-29.7*** (6.8)	0.00
R-squared	0.17		
N of diaries	120,601		

Notes: The model has controls for precipitation, humidity, the characteristics of the respondent and the interview day (gender, age, education, labor market status, household size, day-of-week, public holiday), and county-by-year-by-month fixed effects. Standard errors clustered at the county and individual levels are in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

The effects of temperatures by education

Table A7. The effects of temperatures by education

	Low education	High education	P
	(1)	(2)	(1) vs. (2)
Daily mean temperature (°C)	(1)	(2)	(3)
≤5	3.1** (1.3)	-2.3 (1.9)	0.01
5 to 10	ref. cat.	ref. cat.	
10 to 15	-0.6 (1.6)	-1.9 (2.6)	0.64
15 to 20	-4.9** (1.9)	-1.3 (2.0)	0.12
20 to 25	-8.7*** (2.9)	-3.0 (2.7)	0.08
>25	-17.3*** (3.1)	-10.2** (4.3)	0.13
R-squared	0.17		
N of diaries	120,601		

Notes: The model has controls for precipitation, humidity, the characteristics of the respondent and the interview day (gender, age, education, labor market status, household size, day-of-week, public holiday), and county-by-year-by-month fixed effects. Standard errors clustered at the county and individual levels are in parentheses. * p < 0.10, ** p < 0.05, *** p < 0.01

The effects of temperatures by age

Table A8. The effects of temperatures by age

	Young	Middle-aged	Older	P (1) vs. (2)	P (1) vs. (3)	P (2) vs. (3)
Daily mean temperature (°C)	(1)	(2)	(3)	(4)	(5)	(6)
≤5	-1.7 (2.2)	-0.6 (1.8)	5.4*** (1.8)	0.72	0.04	0.02
5 to 10	ref. cat.	ref. cat.	ref. cat.			
10 to 15	-1.3 (4.2)	-1.5 (1.5)	-0.8 (2.5)	0.98	0.92	0.77
15 to 20	0.4 (2.2)	-4.2* (2.4)	-7.1*** (2.3)	0.05	0.02	0.39
20 to 25	-4.4 (2.9)	-5.4* (3.0)	-8.9* (4.7)	0.77	0.40	0.34
>25	-6.1 (4.5)	-11.9** (5.4)	-26.4*** (3.9)	0.37	0.00	0.03
R-squared	0.17					
N of diaries	120,601					

Notes: The model has controls for precipitation, humidity, the characteristics of the respondent and the interview day (gender, age, education, labor market status, household size, day-of-week, public holiday), and county-by-year-by-month fixed effects. Standard errors clustered at the county and individual levels are in parentheses. * p < 0.10, ** p < 0.05, *** p < 0.01

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The effects of temperatures by gender

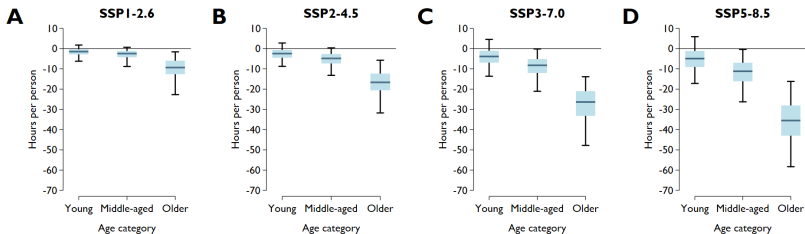
Table A9. The effects of temperatures by gender

	Male	Female	p
	(1)	(2)	(1) vs. (2)
Daily mean temperature (°C)	(1)	(2)	(3)
≤5	0.2 (2.1)	0.3 (1.4)	0.98
5 to 10	ref. cat.	ref. cat.	
10 to 15	-1.5 (2.1)	-1.0 (2.1)	0.85
15 to 20	-3.4* (1.9)	-2.5 (1.9)	0.63
20 to 25	-9.6*** (2.8)	-2.3 (2.6)	0.00
>25	-19.8*** (4.2)	-7.5* (3.8)	0.02
R-squared	0.17		
N of diaries	120,601		

Notes: The model has controls for precipitation, humidity, the characteristics of the respondent and the interview day (gender, age, education, labor market status, household size, day-of-week, public holiday), and county-by-year-by-month fixed effects. Standard errors clustered at the county and individual levels are in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

The elderly will be more severely affected

- ▶ 18-40 year olds -4.9 hours; 41-60 year olds -11.2 hours; older people -35.5 hours (medians, SSP5-8.5, 2090s)

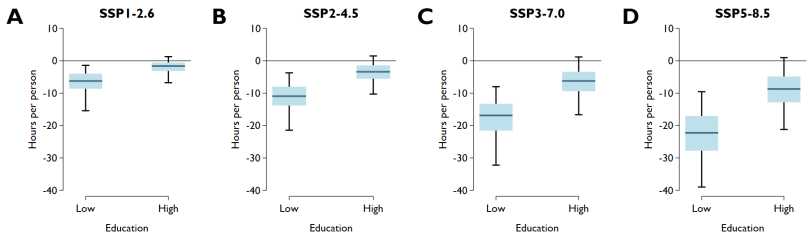


The box plots show the medians, the interquartile ranges, and the middle 95% of the projections.

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Projected annual sleep loss for the 2090s by education

- ▶ The median projection is 22.2 hours for individuals with low education and 8.7 hours for individuals with high education (SSP5-8.5, 2090s)



The box plots show the medians, the interquartile ranges, and the middle 95% of the projections.

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