

Climate Change, Sleep Disruption, and the Gut Microbiome: A Literature-based Predictive Model for Future Human Gut Health

Yumin Lee

The Walker School, 700 Cobb Parkway North, Marietta, GA

Abstract

Global warming has driven a sustained, decades-long rise in both global mean temperature and nighttime minimum temperature. The effects of this warming on the natural environment are widely reported, but its effects on the ecosystem inside the human body remain comparatively little known [1]. This study does not claim that climate change directly alters the gut microbiome. Instead, it reviews, on the basis of the literature, the hypothesized mediated pathway “climate change → rising nighttime temperature → reduced sleep quality → altered gut microbiome → changes in gut health”.

Using 1975-2025 observational data from NASA GISTEMP and Berkeley Earth, this study quantifies the warming trend, and draws on large human sleep studies by Obradovich, Minor, and Li to summarize evidence that nighttime heat reduces sleep duration and sleep efficiency. It then separates human and animal experimental findings to synthesize evidence that sleep loss may affect gut-microbiome diversity and short-chain fatty acid (SCFA) production. Finally, using IPCC SSP scenarios, it presents an exploratory model that projects temperature, sleep loss, and gut-microbiome risk (GMCRI) in five-year steps from 2025 to 2055. This study proposes the new hypothesis that climate change may affect the gut microbiome and gut health through sleep as a mediator.

1. Introduction

In recent years, the phrase “global warming” has appeared in the news almost daily. Temperatures keep rising, heat waves driven by heat domes are intensifying, and stories describing extreme weather as no longer the exception but the new normal have become common. Changes in the external environment-melting glaciers, rising sea levels, shifting ecosystems-are easy to find in newspapers and documentaries.

And yet, curiously, there seems to be relatively little discussion of what climate change may be causing inside our own bodies. The author has come to think that climate change may not only be reshaping the world outside us, but may also be having a considerable, unseen effect on what happens within our bodies. This question first took shape from a personal observation: the author has long had a sensitive digestive system and visits the bathroom frequently, and noticed, on several occasions, that this seemed to get worse during the very summer periods when hot weather made it hard to sleep well. That recurring pattern-poor sleep and poor gut health seeming to arrive together in the hottest weeks of summer-raised a question: could climate change, through the rising temperatures it brings, be

affecting gut health as well?

Of course, it did not seem plausible that temperature could alter gut function directly [2]. Thinking about which part of the body climate change would affect first, and most directly, the answer that emerged was sleep: on hot summer nights, falling asleep was always difficult, and light, frequently interrupted sleep was a recurring experience. Taking this personal experience as a starting point, the following mediated-pathway hypothesis was formulated and the literature was reviewed accordingly.

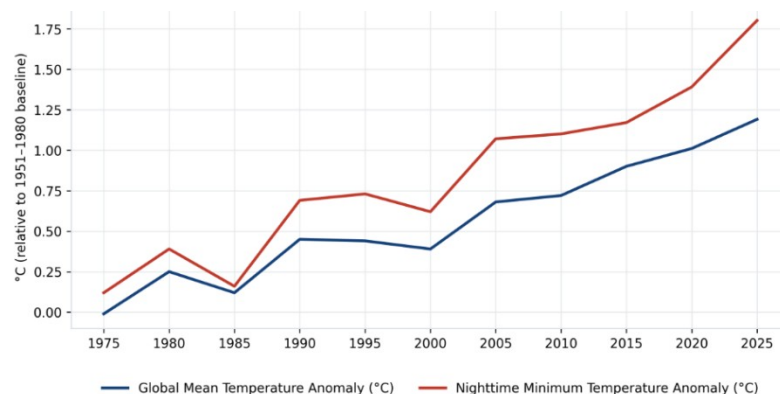
The purpose of this study is not to claim that climate change directly alters the gut microbiome, but to review, on the basis of existing peer-reviewed literature, the possibility that it does so indirectly through the biological mediator of sleep [3], and building on that review, to explore how this may unfold over the next 30 years.

Through the literature review, the following three hypotheses were specifically examined. Hypothesis_1) Nighttime heat reduces an individual's total sleep time and sleep efficiency. Hypothesis_2) Repeated sleep loss is associated with the diversity or functional rhythm of the gut microbiome. Hypothesis_3) Sleep indicators partially mediate the effect between nighttime heat and changes in microbiome function.

2. Global Warming

To check whether this concern is supported by actual data, this study summarizes the 1975-2025 trend using NASA GISTEMP v4's global mean surface temperature anomaly (relative to the 1951-1980 baseline) and Berkeley Earth's land-based daily minimum temperature (TMIN) anomaly [4, 5].

Both datasets show a clear upward trend, and it is notable that nighttime minimum temperature is rising faster than the global mean. The 1975-2025 linear trend works out to roughly 0.207°C per decade. Because sleep is more directly exposed to indoor and outdoor temperature around bedtime than to the daytime maximum, this study uses nighttime



<Figure 1> Comparison of two temperature indicators, 1975–2025 (blue: global mean anomaly; red: nighttime minimum-temperature anomaly). Nighttime minimum temperature is rising more steeply than the global mean. Source: NASA GISTEMP v4; Berkeley Earth.

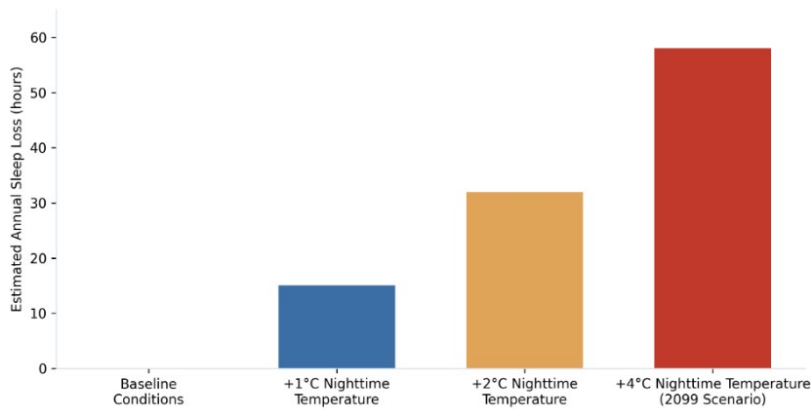
minimum temperature, rather than the global mean, as its core exposure variable (Figure 1).

3. How Temperature Change Affects Sleep

Why is sleep harder to come by on hot nights? For a person to fall asleep, core body temperature must gradually decrease. This drop in body temperature, achieved by releasing heat outward through the hands, feet, and skin, serves as the signal that initiates sleep. When nighttime temperature is high, however, this heat release becomes difficult, which delays sleep onset and reduces the proportion of slow-wave sleep and REM sleep. In addition, the rhythm of melatonin secretion and the circadian rhythm are also known to respond sensitively to temperature change.

Three representative human studies on the relationship between nighttime temperature and sleep are summarized in Table1 [6]. As shown in Figure 2, the increase in temperature and sleep loss exhibits a clear positive relationship, with greater temperature increases being associated with greater sleep loss. This relationship is not a value obtained from a new experiment but is drawn by directly extending Li et al.’s [7] actually published regression coefficient, without inserting any arbitrarily invented intermediate values. The three studies in Table 1 together suggest that nighttime heat may affect not only sleep duration but also sleep efficiency, the number of awakenings, and the proportion of deep sleep. Because reduced sleep can, in turn, lead to a range of downstream effects-reduced concentration, metabolic changes, and altered immune function-this study chose to focus its literature review specifically on the gut microbiome. The reason is that this outcome is most directly connected to the personal experience described in the introduction, namely the co-occurrence of summer sleep loss and worsened gut condition.

<Table 1> Major human studies on the relationship between nighttime temperature and sleep



<Figure 2> Relationship between increasing nighttime temperature and estimated annual sleep loss. The graph was reconstructed from values reported by Minor et al. (2022) [8] and is presented as a schematic illustration.

Study	Sample/ Design	Key Findings
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Obradovich et al., 2017	~765,000 U.S. survey respondents (2002–2011)	Higher nighttime temperature anomalies were associated with more frequent reports of “insufficient sleep”
Minor et al., 2022	47,628 people in 68 countries; over 7 million wearable sleep records	Warmer nights delayed sleep onset and shortened sleep duration; projected annual sleep loss of 50–58 hours by 2099
Li et al., 2025	23 million person-days of repeated measures in China	Each 10°C rise in mean temperature reduced total sleep time by 9.67 minutes and raised the odds of insufficient sleep by 20.1%

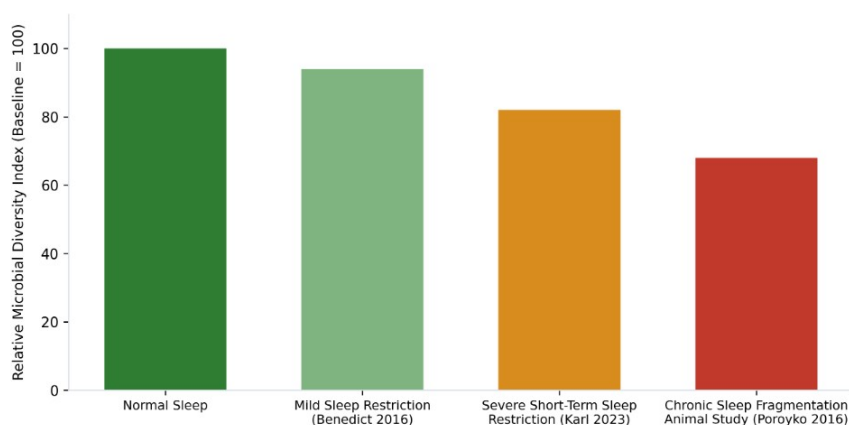
4. Sleep induced changes in the gut microbiome

Human studies on the relationship between sleep and the gut microbiome remain few in number [9], and their findings do not fully agree with one another. To address this limitation, this chapter clearly distinguishes human studies from animal (mainly mouse) studies and reviews them together.

Taken together, the changes most frequently reported in connection with sleep loss are as follows. First, shifts in the Firmicutes/Bacteroidetes ratio. Second, a decrease in beneficial gut bacteria such as *Faecalibacterium*, *Roseburia*, and *Akkermansia*. Third, a decline in the short-chain fatty acids (SCFAs, particularly butyrate) that these bacteria produce. Fourth, weakened intestinal tight-junction function leading to increased gut permeability and elevated systemic inflammation (IL-6, TNF-alpha, and others).

As Table2 below shows, individual links along the proposed pathway carry very different levels of evidentiary strength, and this study evaluates each link separately rather than folding the entire pathway into a single conclusion.

As this evidence table shows, Karl et al.’s (2023) human experiment [10] and Poroyko et al.’s (2016) mouse experiment [11] agree in the direction of decreased diversity, while Zhang et



<Figure 3> Relative microbial diversity under different sleep conditions. The figure conceptually summarizes the proposed pathway from sleep disruption to reduced microbial diversity and potential gut-health effects, based on Poroyko et al. (2016) [11], Benedict et al (2016) [12], and Karl et al. (2023) [10].

<Table 2> Comparison of human and animal studies on sleep and the gut microbiome

Study	Subjects	Sleep intervention	Gut-microbiome change	Notes
Zhang et al., 2017	Humans + mice	Several days of sleep restriction	No clear change in overall community composition	A null result contrary to the hypothesis, included for balance
Poroyko et al., 2016	Mice	4 weeks of sleep fragmentation	Microbiome changes plus visceral-fat inflammation and insulin resistance	Strong mechanism, but limited human extrapolation
Benedict et al., 2016	Humans, crossover design	Acute sleep restriction	Subtle compositional changes and altered metabolic responses	Small sample, short duration
Karl et al., 2023	Healthy adult men	Severe short-term sleep restriction	Reduced diversity (richness); no change in permeability	Human experiment, limited sample size
Smith et al., 2019	Humans, observational	Everyday sleep physiology	Association between diversity and sleep efficiency/duration	Cross-sectional, reverse causation possible

al. (2017) [13] and Smith et al. (2019) [14] found no significant change or produced mixed results. Because different studies reach different conclusions, forcing the numbers from different studies onto a single shared scale could be more misleading than informative. Therefore, this study attempted to examine the relationship between sleep quality and changes in the gut microbiome by considering findings from animal studies alongside evidence from human studies.

5. Projected changes (2025-2055)

This chapter uses IPCC AR6 SSP scenarios to explore [15], in five-year steps from 2025 to 2055, the projected rise in temperature, expected sleep loss, and gut-microbiome risk. For this purpose, the author proposes an exploratory index that combines temperature, sleep, microbiome diversity, SCFA, and inflammatory markers into a single scale: the Gut Microbiome Climate Risk Index (GMCRI, 0-100).

The SSPs (Shared Socioeconomic Pathways) used here are the standard scenario framework the IPCC uses to project the future; the number following "SSP" indicates the approximate radiative forcing (the additional heat the planet retains due to greenhouse gases, in W/m²) expected around the year 2100. A larger number corresponds to a future with greater greenhouse-gas emissions. In simple terms, SSP1-2.6 is a low-carbon scenario with active emissions reduction, SSP2-4.5 is an intermediate scenario in which roughly current efforts continue, and SSP5-8.5 is a high-carbon scenario in which fossil-

fuel dependence continues with little mitigation.

This study compares these three scenarios side by side to show how future risk might differ depending on the degree of greenhouse-gas reduction achieved.

Before presenting the calculations, it is worth first clarifying what a rigorous climate-sleep-microbiome prediction would actually require. Directly forecasting the specific composition of the gut microbiome in 2055 from current literature alone is difficult to justify scientifically. Instead, it is more appropriate to project, scenario by scenario, the conditional changes in “nighttime heat exposure → sleep loss → microbiome and inflammatory indicators”, propagating the uncertainty from each stage to the next. The recommended five-stage prediction framework for this purpose is shown in Table3.

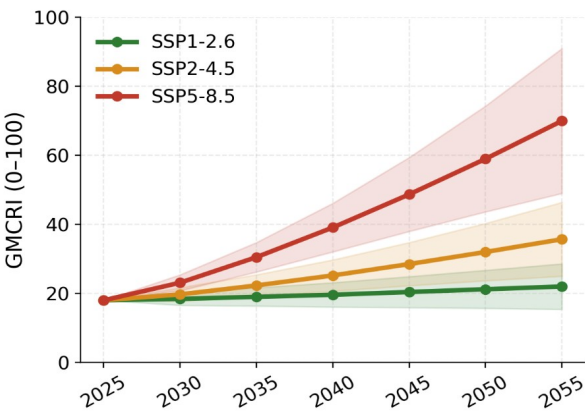
Because this study is at the literature-review stage, without directly available microbiome or health data, it did not implement all five stages above. Instead, it used a simplified proxy model that connects only ① temperature and ② sleep loss through real coefficients, while representing ③ the microbiome response with a single non-linear function (GMCRI). This simplified approach should be replaced with a Bayesian hierarchical model and Monte Carlo uncertainty propagation once repeated-measures cohort data become available in future research.

Rather than inventing predicted values arbitrarily, this study calculated them by starting from real published figures, through the following three steps.

① Baseline conversion: NASA GISTEMP’s temperature anomaly uses 1951-1980 as its baseline, whereas the IPCC AR6 SSP scenario estimates (1.8/2.7/4.4°C) use 1850-1900 as their baseline. According to NASA data, the difference between these two baselines was about 0.19°C as of 2024, and this offset was used to convert both datasets onto a common baseline.

② Sleep-loss coefficient: This study used a single anchor value-Minor et al.’s (2022) reported figure of “up to 58 hours of annual sleep loss by 2099 under continued warming”.

<Table 3> Recommended five-stage framework for quantifying the climate-sleep-microbiome-health



<Figure 4> Projected GMCRI trajectories by SSP scenario, 2025–2055. Green: SSP1-2.6; orange: SSP2-4.5; red: SSP5-8.5. The shaded band shows the uncertainty range widening over time (±10% → ±30%); the curvature reflects the non-linear formula described in Section 5.

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Stage	Recommended data / model	Output
Climate	CMIP6 SSP1-2.6/2-4.5/5-8.5 ensemble + bias correction and downscaling	2071–2080 distribution of nighttime temperature and tropical nights
Sleep	Distributed lag non-linear model (DLNM) or GAMM exposure-response model	Individual- and region-level sleep loss / probability of insufficient sleep
Microbiome	Bayesian hierarchical longitudinal mediation (joint) model	Probability distribution of change in diversity, functional pathways, and metabolites
Health	Microsimulation or multistate model	Scenario-specific differences in obesity, diabetes, and cardiovascular risk
Uncertainty	Monte Carlo simulation with multi-model climate ensemble	95% prediction interval and sensitivity analysis

Dividing this figure by the additional warming expected under SSP5-8.5 from 2025 to 2099 (about 3.0°C) yields a single proportional coefficient of roughly 19.2 hours of annual sleep loss per 1°C, which was applied uniformly across all scenarios and years.

③ Non-linear GMCRI transformation: Because real biological stress is reported to intensify more steeply as exposure accumulates (the non-linearity of chronic cumulative stress), GMCRI was set to scale not linearly but with sleep loss raised to the power of 1.3 ($GMCRI = 18 + 0.725 * \text{sleep-loss}^{1.3}$). This exponent was back-calculated so that the SSP5-8.5 value for 2055 equals 70; it is explicitly not a validated biological constant but an exploratory assumption set by the author. To reflect the fact that uncertainty grows the further into the future the projection extends, the shaded region in Figure 4 shows an uncertainty range that widens from $\pm 10\%$ in 2030 to $\pm 30\%$ in 2055.

In all three scenarios, GMCRI rises over time, but the rate of increase is not constant- it accelerates in a non-linear fashion further into the future. Under SSP5-8.5, where mitigation efforts are insufficient, the 2055 GMCRI (70.0) is roughly 3.9 times the 2025 value (18.0), whereas under SSP1-2.6 the same period sees a comparatively gentle rise to 22.0. This is not a precise prediction of actual microbiome change, but a visualization-together with its uncertainty-of the possibility that “if warming continues, gut-health risk mediated by sleep could grow increasingly faster over time”. In terms of health, the literature raises the possibility that, if chronic sleep loss and reduced gut-microbiome diversity accumulate, risks such as metabolic syndrome, systemic inflammation, and gastrointestinal symptoms could rise together.

6. Discussion, Limitation and Conclusion

6.1 Overall Discussion

This study does not claim that climate change directly alters the gut microbiome. Instead, it is a literature-based study that synthesizes existing peer-reviewed literature to propose the

mediated-pathway hypothesis “climate change → rising nighttime temperature → reduced sleep → altered gut microbiome → changes in gut health”. The strength of evidence differs across each link. The relationship between warming and rising nighttime temperature rests on very strong observational evidence, but the relationship between sleep and the gut microbiome still shows inconsistent results in human research and should be treated as “hypothetical”.

6.2 Limitations

This study has the following clear limitations. First, few studies have tracked temperature, sleep, and the gut microbiome simultaneously in humans over a long period. Second, the gut microbiome varies enormously between individuals. Third, many confounding factors exist, including diet, antibiotic use geographic location, and socioeconomic status. Fourth, GMCRI is not a validated clinical indicator but an exploratory conceptual index proposed in this study. Fifth, the climate models (SSP scenarios) used for future projection carry their own uncertainty.

6.3 A Personal Closing Note

This study began from a personal concern about frequent bathroom visits. What started as a simple curiosity turned, as the literature was reviewed one study at a time, into the discovery that a genuine body of scientific interest connects temperature and sleep, and sleep and the gut microbiome. At the same time, it became clear how much remains unproven.

6.4 What Should We Do?

There may not be much that can be done immediately. Still, managing the sleep environment on hot nights through cooling or ventilation, and paying attention to greenhouse-gas reduction efforts, are both things that can be practiced at the individual level. Academically, long-term cohort studies that track temperature, sleep, and the gut microbiome together are needed going forward.

6.5 Conclusion

Climate change may affect not only the natural environment but also the human internal ecosystem, through the pathway of sleep and the gut microbiome. This study has synthesized existing literature supporting this possibility to propose a new hypothesis, and future research should extend its view to include this internal human ecosystem as well.

References

1. Wibowo, M. C., et al. (2021). Reconstruction of ancient microbial genomes from the human gut. *Nature*, 594, 234–239. <https://doi.org/10.1038/s41586-021-03532-0>
2. Wen, S., et al. (2021). Experimental heat stress alters mouse intestinal microbiota and metabolites. *Frontiers in Microbiology*. <https://doi.org/10.3389/fmicb.2021.706772>
3. Litchman, M. (2025). Direct and indirect climate-change pathways affecting the

human gut microbiome. *Lancet Planetary Health*. [https://doi.org/10.1016/S2542-5196\(24\)00332-2](https://doi.org/10.1016/S2542-5196(24)00332-2)

4. NASA GISTEMP v4. Global surface temperature anomaly data, 1880–present. NASA Goddard Institute for Space Studies. <https://data.giss.nasa.gov/gistemp>
5. Berkeley Earth high-resolution TMIN. Annual land average of daily minimum temperature anomalies. <https://berkeleyearth.org/data>
6. Obradovich, N., Migliorini, R., Mednick, S. C., & Fowler, J. H. (2017). Nighttime temperature and human sleep loss in a changing climate. *Science Advances*, 3(5), e1601555. <https://doi.org/10.1126/sciadv.1601555>
7. Li, Y., et al. (2025). Climate warming may undermine sleep duration and quality: a repeated-measure study of 23 million records. *Nature Communications*. <https://doi.org/10.1038/s41467-025-57781-y>
8. Minor, K., Bjerre-Nielsen, A., Jonasdottir, S. S., Lehmann, S., & Obradovich, N. (2022). Rising temperatures erode human sleep globally. *One Earth*, 5(5), 534–549. <https://doi.org/10.1016/j.oneear.2022.04.008>
9. Withrow, D., et al. (2021). Sleep and circadian disruption and the gut microbiome — possible links to dysregulated metabolism. *Current Opinion in Endocrine and Metabolic Research*, 17, 35–40. <https://doi.org/10.1016/j.coemr.2020.11.004>
10. Karl, J. P., et al. (2023). Severe, short-term sleep restriction reduces gut microbiota diversity in healthy adults. *Scientific Reports*, 13, 2700. <https://doi.org/10.1038/s41598-023-27463-0>
11. Poroyko, V. A., et al. (2016). Chronic sleep disruption alters gut microbiota, induces systemic and adipose tissue inflammation and insulin resistance in mice. *Scientific Reports*, 6, 35405. <https://doi.org/10.1038/srep35405>
12. Benedict, C., et al. (2016). Gut microbiota and glucometabolic alterations in response to recurrent partial sleep deprivation in normal-weight young individuals. *Molecular Metabolism*, 5(12), 1175–1186. <https://doi.org/10.1016/j.molmet.2016.10.003>
13. Zhang, S. L., et al. (2017). Human and rat gut microbiome composition is maintained following sleep restriction. *PNAS*, 114(8), E1564–E1571. <https://doi.org/10.1073/pnas.1620673114>
14. Smith, R. P., et al. (2019). Gut microbiome diversity is associated with sleep physiology in humans. *PLOS ONE*, 14(10), e0222394. <https://doi.org/10.1371/journal.pone.0222394>
15. IPCC AR6 Synthesis Report (2023). *Climate Change 2023: Synthesis Report*. <https://www.ipcc.ch/report/ar6/syr/>