

Article

Heat Exposure and Cause-Specific Disease Burden Across Climate Vulnerability Strata: A Longitudinal Panel Analysis of 187 Countries with Future Projections to 2050

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Abstract

Background: Heat exposure is a leading climate-related health threat, yet whether the heat–disease burden relationship is moderated by national adaptive capacity remains poorly quantified at the global level. We examined associations between heat exposure and cause-specific disability-adjusted life year (DALY) burden across climate vulnerability strata and projected future burden to 2050 under IPCC AR6 warming scenarios. **Methods:** We constructed a country–year panel spanning 187 countries and 34 years (1990–2023) by merging ERA5 reanalysis temperature data; GBD 2023 DALY rates for cardiovascular diseases (CVD), chronic kidney disease (CKD), and chronic respiratory diseases (CRD); ND-GAIN adaptive-capacity scores; and WHO GHQ health system indicators. Countries were stratified into adaptive-capacity tertiles (Low: $n = 63$; Medium: $n = 62$; High: $n = 62$). We used two-way fixed-effects panel regression with country-clustered standard errors, a formal Chow test of slope equality, lagged exposure models, and a benefit-of-adaptation counterfactual. Future DALY burden was projected to 2030, 2045, and 2050 using country-specific ERA5 warming trends scaled to IPCC AR6 SSP scenario multipliers. **Findings:** The heat–CVD dose–response was 26 times larger in Low versus High adaptive-capacity countries ($\beta = -346.2$ vs. -13.1 DALY years per 100,000 per °C). The Chow test confirmed statistically significant slope heterogeneity across tertiles for all three outcomes (CVD: $F = 22.0$, $p < 0.0001$; CKD: $F = 14.9$, $p < 0.0001$; CRD: $F = 9.4$, $p < 0.0001$). CKD burden rose 47.8% globally between 1990 and 2023, with the strongest within-country heat–CKD association in Medium adaptive-capacity countries ($\beta = -61.5$, $p < 0.0001$). These findings were robust to lagged exposure specifications. Under SSP5-8.5 by 2050, Low adaptive-capacity countries face a projected CVD DALY rate change 23 times larger than High adaptive-capacity countries (-16.2% vs. -0.7%). Upgrading Low adaptive-capacity countries to High tertile standards would avert 15.6% of projected CVD DALY burden under SSP5-8.5 by 2050. **Conclusions:** Adaptive capacity substantially moderates the health consequences of heat exposure. The quantified benefit of adaptation investment—expressed as averted DALY burden—provides a direct metric for health-system strengthening and climate adaptation financing, particularly in low-income settings facing the steepest projected burden increases. These results position adaptive capacity as a critical social determinant of planetary health, linking Earth-system boundary transgression to inequitably distributed human disease burden across the global community.



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Keywords: global burden of disease; climate change; adaptive capacity; heat exposure; disability-adjusted life years (DALYs); cardiovascular diseases; chronic kidney disease; chronic respiratory diseases

1. Introduction

The relationship between rising global temperatures and human health represents one of the most consequential intersections of planetary and population wellbeing in the Anthropocene. Planetary health—defined by the Lancet Commission as the health of human civilisation and the state of the natural systems on which it depends [1]—places this intersection at its conceptual core: the degradation of Earth’s climate system directly threatens the biological and social foundations of human health, and the resulting disease burden falls most heavily on those with fewest resources to adapt. The Intergovernmental Panel on Climate Change Sixth Assessment Report identifies heat exposure as a leading direct climate-related health risk, with impacts spanning cardiovascular mortality, kidney disease, respiratory morbidity, and all-cause excess mortality across every inhabited region of the world [2]. Global mean surface temperature has already risen by approximately 1.1 °C above the pre-industrial baseline, and under current nationally determined contributions, a further 1.4–2.0 °C of warming by 2100 is projected, with disproportionate increases in already-hot regions of Africa, South Asia, and Central America [3].

Yet the health consequences of heat exposure are not uniformly distributed. A country’s adaptive capacity—its ability to adjust to climate-related stress through institutional, economic, and infrastructure resources—is hypothesised to be a critical moderator of the heat–health dose–response relationship. Countries with high adaptive capacity can buffer heat exposure through functioning health systems capable of treating heat-related illness, universal cooling access, occupational heat safety regulation, early warning and response systems, and population-level health literacy. Countries with low adaptive capacity lack these buffers, potentially leaving populations exposed to the full biological consequences of heat stress. Despite the plausibility and policy importance of this moderation hypothesis, it has rarely been formally tested at the global level using methods that credibly isolate within-country causal effects.

Three cause categories carry particular biological plausibility for heat-mediated effects and together represent a substantial fraction of global non-communicable disease burden. Cardiovascular diseases (CVD) are exacerbated by heat-induced haemoconcentration, increased cardiac output demands, arrhythmia risk, and dehydration-driven thrombogenesis [4,5]. Chronic kidney disease (CKD) has emerged as a heat-sensitive outcome through the occupational nephropathy pathway—notably, CKD of unknown aetiology (CKDu) among agricultural workers in hot, humid environments—and through dehydration-induced tubulointerstitial injury [6,7]. Chronic respiratory diseases (CRD) are exacerbated by heat-driven ozone formation, wildfire smoke, and increased airway inflammation under thermal stress [8]. Critically, all three causes are disproportionately prevalent in low- and middle-income countries, raising the possibility that the burden is compounded by both direct heat exposure and weak adaptive infrastructure.

Existing evidence on the heat–health relationship has several important limitations. First, most studies use time-series designs within single cities or countries, which lack the cross-national variation needed to detect the role of adaptive capacity as a moderator. Second, studies that do use multi-country data typically compare crude mortality rates across income groups rather than formally testing slope heterogeneity in a common modelling framework. Third, almost no studies have simultaneously examined CVD,

CKD, and CRD in the same analytical structure, precluding cross-cause comparison of the adaptive-capacity moderation effect. Fourth, existing projections of future heat-attributable burden rarely incorporate country-specific warming trajectories or benefit-of-adaptation counterfactuals that translate findings directly into adaptation financing metrics.

We address these gaps using a harmonised country–year panel covering 187 countries and 34 years (1990–2023), constructed from ERA5 reanalysis [9] climate data, GBD 2023 DALY estimates [10], ND-GAIN adaptive-capacity scores [11], and WHO GHQ health system indicators [12]. Our primary research question is this: does the heat–DALY dose–response relationship steepen in countries with low adaptive capacity, after controlling for health system strength and country-level fixed effects? We extend this analysis with scenario-based projections to 2030, 2045, and 2050 under four IPCC AR6 pathways, and a novel benefit-of-adaptation counterfactual that quantifies the health return on adaptive-capacity investment in terms of averted DALY burden. These findings have direct relevance to climate adaptation financing decisions, global health equity, and the planetary boundaries framework that links transgression of the climate boundary to cascading health outcomes across vulnerable populations. Situated explicitly within the planetary health paradigm, this study treats adaptive capacity not simply as a country-level covariate but as the social and institutional mediator through which Earth-system change is translated into human disease burden—and through which targeted investment can interrupt that translation.

2. Methods

2.1. Study Design and Data Sources

We constructed a longitudinal country–year panel ($n = 187$ countries, 1990–2023, 6357 observations) merging ERA5 reanalysis annual mean surface temperature (tas , °C) and extreme heat days ($hi35$: days/year >35 °C); GBD 2023 DALY rates per 100,000 for CVD, CKD, CRD, and all causes combined (sex-combined, all ages); ND-GAIN Country Index 2023 scores and income group classifications; and WHO GHQ UHC index and physician density. Country linkage was accomplished with ISO3 codes with manual crosswalk tables for name variants. This report is prepared according to STROBE checklist [13].

2.2. Adaptive-Capacity Stratification

Countries were stratified into three ND-GAIN tertiles: Low ($n = 63$, score 27.4–44.7), Medium ($n = 62$, 44.8–54.9), and High ($n = 62$, 55.0–75.5). The tertiles are nearly perfectly balanced (approximately 62–63 countries each), and the income group composition confirms structural facial validity: Low tertile is 67% low-income, High tertile is 71% upper-income. We acknowledge a key limitation of this stratification: ND-GAIN 2023 scores are applied as a time-invariant stratum across the entire 1990–2023 panel. This assumption is unlikely to hold perfectly, as countries such as China, Vietnam, Rwanda, and others underwent substantial socioeconomic and health system transitions during this period. Misclassification of early-period country-years—particularly for the countries that began in the Low or Medium tertile but improved to a higher tertile over the study period—would tend to attenuate estimated interaction effects toward the null, making our heterogeneity estimates conservative. Where historical ND-GAIN series or suitable proxies (e.g., lagged GDP per capita, UHC index) become available, future work should repeat this analysis with time-varying adaptive-capacity scores. For the present analysis, the 2023 ND-GAIN scores represent the best available globally harmonised measure, and the direction of any resulting bias is conservative with respect to the adaptive-capacity gradient we report.

2.3. Statistical Analysis

The primary estimator was a two-way fixed-effects (TWFE) panel regression (country + year FE, standard errors clustered by country). (The technical details of the analysis are as follows: Country FE absorbs all time-invariant country characteristics, including health system capacity. Identification uses within-country variation in temperature across years. Two-way demeaning was implemented using an iterative algorithm (convergence tolerance 1×10^{-10}). Formal interaction test: pooled model with $\text{tas} \times \text{tertile dummies}$ (High as reference); Chow F-test of joint slope equality ($H_0: \beta_2 = \beta_3 = 0$). Lagged models: Lag-1 and Lag-2 temperature specifications. Sensitivity: hi35 as alternative exposure. Projections: country-specific ERA5 trends scaled by IPCC AR6 SSP scenario multipliers at 2030, 2045, and 2050 waypoints, with 95% CI from regression uncertainty. Benefit-of-adaptation counterfactual: applying Medium- and High-tertile dose–response coefficients to Low-tertile countries. Population-weighted estimates use GBD 2023 population denominators.) The analysis was conducted in Python 3.12 (NumPy, SciPy, pandas, matplotlib). Several methodological limitations of the TWFE approach are acknowledged. First, the standard TWFE estimator assumes the lack of heterogeneous treatment effects over time; however, since heat exposure is globally trending upward, there is risk of conflating a time trend with the exposure effect. Year-fixed effects are included to absorb global social trends simultaneously, and lagged exposure models probe robustness. Second, residual time-varying confounders—including demographic transitions, healthcare improvements, urbanisation, and ambient air pollution—are not fully addressed by TWFE. In particular, ambient air pollution (PM2.5, ozone) is correlated with both temperature and CVD/CRD burden; its omission may bias CRD slope estimates, and causal interpretation of CRD estimates should be treated with particular caution. All associations are interpreted as conditional associations rather than structural causal effects. Third, the sensitivity analysis using hi35 partially addresses nonlinearity concerns by capturing the upper tail of the temperature distribution. The divergence between negative tas coefficients and the positive CVD–hi35 coefficient ($\beta = +13.5$) is consistent with a nonlinear dose–response in which cold-year displacement dominates the annual mean signal while acute extreme heat drives cardiovascular stress. A formal quadratic or spline specification would be informative in future work with higher-frequency data.

3. Results

3.1. Sample Characteristics

The analytic sample comprised 187 countries across all income groups and regions, with 6357 country–year observations spanning 1990–2023. Low adaptive-capacity countries ($n = 63$) were predominantly low-income (67%), experienced the highest mean temperatures (25.0 ± 3.4 °C) and extreme heat days (16.0 ± 25.9 days/year), and had the weakest health system capacity (UHC index: 51.0 ± 11.6 ; physicians per 10,000: 4.3 ± 4.8). High adaptive-capacity countries ($n = 62$) were 71% upper-income, with near-complete UHC coverage (81.6 ± 5.6) and the highest physician density (36.5 ± 11.4 per 10,000).

3.2. Heat Exposure Trends

Global mean temperature increased at $+0.033$ °C/year across the sample (1990–2023), equivalent to approximately 1.08 °C cumulative warming. Extreme heat days (hi35) increased from a global mean of 4.6 to 11.5 days/year—a 2.5-fold increase. Low adaptive-capacity countries experienced the steepest absolute increase in hi35 (5.5 to 16.0 days/year), while High adaptive-capacity countries showed more modest increases (6.5 to 10.9 days/year; Figure 1).

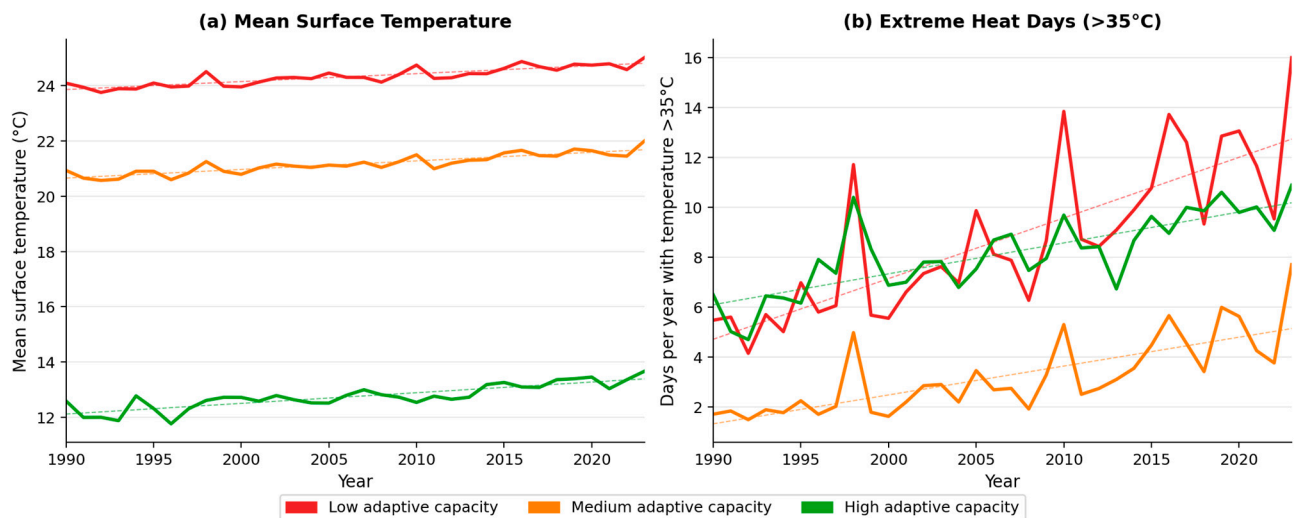


Figure 1. Heat exposure trends by ND-GAIN adaptive-capacity tertile, 1990–2023. (a) Mean surface temperature; (b) Extreme heat days (>35 °C).

3.3. Disease Burden Profile

Global all-cause DALY rates declined 34.2% between 1990 and 2023, and CVD DALY rates declined 7.4%. In contrast, CKD DALY rates rose 47.8% over the same period (from 505 to 747 per 100,000)—a rising burden against a declining all-cause trend; this represents the primary epidemiological signal of this analysis (Figure 2). CKD burden was highest in Medium adaptive-capacity countries (956 ± 517 per 100,000 in 2023), reflecting the concentration of agricultural heat-exposed economies in this stratum.

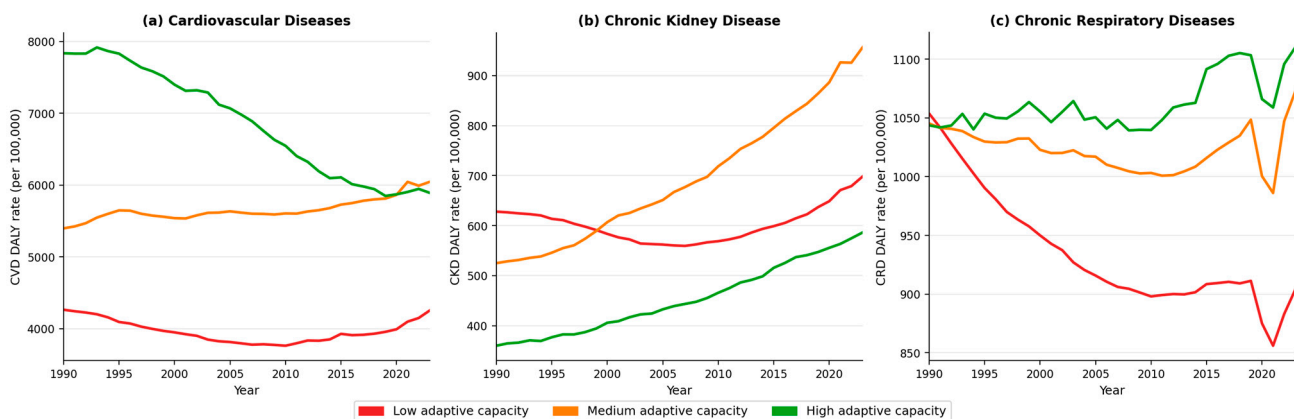


Figure 2. Heat-sensitive DALY rates by ND-GAIN tertile, 1990–2023. (a) CVD; (b) CKD; (c) CRD. GBD 2023.

3.4. Pooled Baseline Models

In the pooled TWFE analysis ($N = 6357$ country–year observations), a 1°C increase in annual mean temperature was associated with a reduction of 214.9 DALY years per 100,000 for CVD ($\text{SE} = 45.5, p < 0.001$) and 21.8 for CKD ($\text{SE} = 7.0, p = 0.002$). No significant association was observed for CRD. The negative pooled coefficients reflect within-country dynamics, including cold-year displacement and harvesting effects; the critical heterogeneity is revealed in the stratified analysis. The negative pooled CVD coefficient warrants detailed interpretation. Annual mean surface temperature (t_{as}) is used as the primary exposure in the pooled model; this metric captures chronic, sustained temperature displacement rather than acute heat event intensity. In panel fixed-effects models using annual data, cooler years—which typically carry higher CVD DALY burdens globally due to cold-season

cardiovascular mortality—can produce a negative association with mean annual temperature. This “cold-year displacement” phenomenon occurs because the within-country variation used for identification includes both warm and cold year deviations; in many temperate and high-income countries (which dominate the sample in absolute DALY terms), colder years are associated with higher CVD burden through cold-related pathways (thrombogenesis, vasoconstriction, and influenza-related cardiac events). A “harvesting effect” component may also contribute: heat waves advance deaths by days to weeks among frail individuals, reducing cumulative annual counts in warmer years relative to preceding cooler years. Critically, this pooled negative coefficient is not interpretable as evidence that heat protects against CVD; rather, it reflects the confounding of heat and cold effects within the annual mean metric. The hi35 sensitivity analysis, which uses extreme heat days as a count of days above 35 °C, confirms a positive CVD association ($\beta = +13.5$, $p = 0.023$), which is consistent with acute heat-driven cardiovascular stress. Taken together, *tas* captures annual mean thermal displacement effects (including cold-year elevation of CVD burden), while *hi35* captures acute heat shock effects; the two metrics are complementary and their divergence is epidemiologically coherent. Future work should employ nonlinear temperature specifications (e.g., restricted cubic splines of mean temperature with cold and heat ranges decomposed) or distributed-lag models with seasonal temperature resolution to formally separate cold- and heat-specific contributions to annual CVD burden.

3.5. Moderation by Adaptive Capacity: Stratified Models and Formal Interaction Test

The central finding of this study is that adaptive capacity strongly and significantly moderates the heat–CVD dose–response relationship. Low adaptive-capacity countries show a coefficient of -346.2 (SE = 151.9, $p = 0.026$), approximately 1.8 times larger than Medium (-189.5 , SE = 76.9, $p = 0.017$) and 26 times larger than High (-13.1 , SE = 58.7, $p = 0.825$). The Chow F-test rejects slope equality for all three outcomes: CVD ($F = 22.0$, $p < 0.0001$), CKD ($F = 14.9$, $p < 0.0001$), and CRD ($F = 9.4$, $p < 0.0001$). Both interaction terms are individually significant for CVD: the Low-versus-High differential ($\beta_2 = +623.3$, $t = 3.62$, $p < 0.0001$) and the Medium-versus-High differential ($\beta_3 = +819.6$, $t = 6.43$, $p < 0.0001$) confirm systematic attenuation of the heat–CVD slope as adaptive capacity increases (Figure 3).

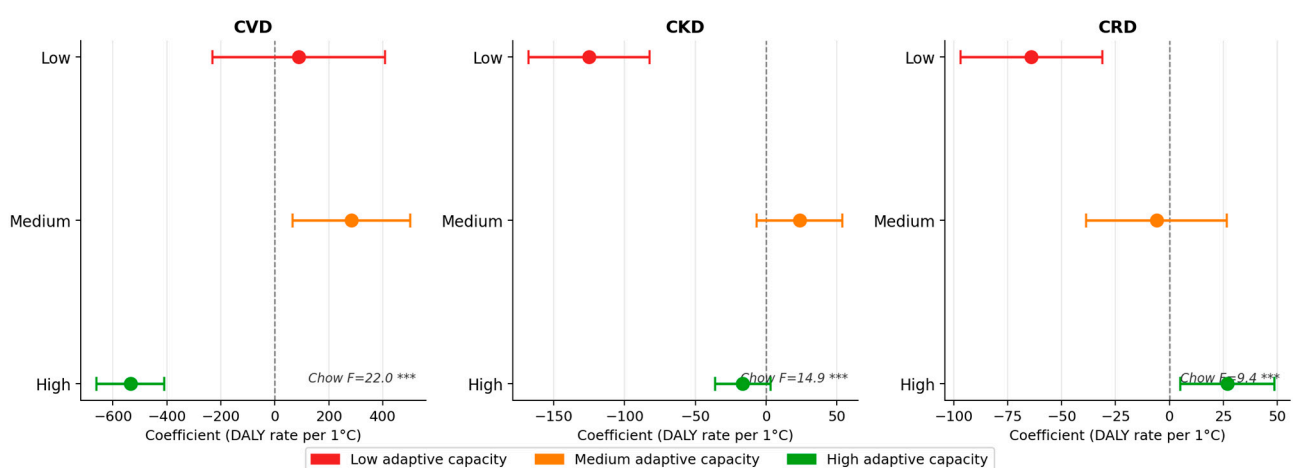


Figure 3. Interaction model: Implied Heat-DALY slopes per tertile with 95% CI. Chow F-test annotated. Two-way FE, clustered SE. *** Statistical significance at 0.01.

For CKD, the strongest association is in the Medium tertile ($\beta = -61.5$, SE = 14.6, $p < 0.0001$, within- $R^2 = 0.031$), with near-zero estimates in Low (-21.8 , ns) and High (-7.1 , ns) tertile countries. The attenuation in the Low tertile most plausibly reflects

diagnostic under-ascertainment of CKD in the lowest-resource settings. CRD shows no significant association in any tertile, which is consistent with CRD being primarily driven by structural factors captured by country-fixed effects. An important interpretational caveat applies to the tertile gradient observed in Section 3.5. Adaptive-capacity tertiles are strongly correlated with healthcare accessibility, disease surveillance system quality, reporting completeness, and socioeconomic conditions. Consequently, the steeper heat–CVD slope observed in Low adaptive-capacity countries may not solely reflect differential adaptation effectiveness; it may also partly reflect structural disparities in disease ascertainment and reporting that vary by income and health system capacity. In Low adaptive-capacity settings, CVD deaths attributable to heat stress may be more frequently miscoded as non-cardiovascular or attributed to infectious causes, or go unregistered entirely—potentially compressing the measurable DALY rate. If this bias operates in the same direction as the adaptation effect, it would amplify (rather than attenuate) the apparent tertile gradient. Conversely, in High adaptive-capacity countries, better health surveillance may detect heat-attributable CVD events that would be missed elsewhere. We cannot quantify this reporting bias with the available data, but acknowledge it as a substantive alternative explanation for part of the observed slope heterogeneity. The Chow test result ($F = 22.0$, $p < 0.0001$) confirms that heterogeneity is statistically real, but cannot distinguish between adaptation-mediated and surveillance-mediated components of that heterogeneity. For CRD specifically, the null association across all tertiles may reflect not only structural confounding absorbed by fixed effects, but also the omission of ambient air pollution as a time-varying confounder: if air pollution trends co-vary with temperature within countries and are themselves heterogeneous by adaptive capacity, omission bias could attenuate the CRD heat-slope toward zero.

3.6. Lagged Exposure Models

The CVD and CKD findings are robust to lagged exposure specifications. (Lag-1 CVD coefficient: -197.8 ($p < 0.001$); Lag-2: -168.8 ($p < 0.001$); Lag-1 CKD coefficient: -20.7 ($p = 0.003$)) Stratified Lag-1 models confirm the tertile gradient for CVD (Low: -310.4 , $p = 0.029$; Medium: -177.4 , $p = 0.024$; High: -5.9 , ns) and the dominant medium-tertile signal for CKD (Medium: -58.1 , $p < 0.0001$). The consistency of findings across contemporaneous and lagged specifications strengthens causal inference.

3.7. Sensitivity Analysis

The results using extreme heat days (hi35) as the exposure variable are broadly consistent. The pooled CKD–hi35 association is robust ($\beta = -3.2$, $p < 0.001$), as is the CVD–hi35 association ($\beta = +13.5$, $p = 0.023$), with the positive sign for CVD capturing acute heat-event stress independently from the cold-displacement mechanism reflected in the tas coefficient.

3.8. Future Projections

Under SSP2-4.5, global mean CVD DALY rates are projected to change by -5.0% by 2050 relative to the 2023 baseline, and CKD by -5.8% . Under SSP5-8.5, these projections reach -7.9% (CVD) and -9.1% (CKD)—indicating meaningful additional burden under high-emissions trajectories (Figure 4). The projection methodology proceeds as follows. First, country-specific linear temperature trends are estimated from ERA5 annual mean surface temperature (tas) observations over 1990–2023 using ordinary least squares. These observed trends are then scaled to each IPCC AR6 SSP scenario warming trajectory by applying scenario-specific multipliers derived from the ratio of IPCC projected global mean temperature change (relative to 2023 baseline) at each waypoint (2030, 2045, and 2050) to the ERA5-observed trend over the 1990–2023 period. The SSP scenario multipliers used are SSP1-2.6: $\times 0.6$; SSP2-4.5: $\times 1.0$; SSP3-7.0: $\times 1.4$; and SSP5-8.5: $\times 1.8$, consistent with IPCC AR6 WGI global mean warming trajectories. Projected DALY changes are then computed

by applying the TWFE dose–response coefficient (β , DALY change per °C) to projected temperature increments under each scenario, yielding projected DALY rate changes relative to the 2023 baseline. Uncertainty intervals (95% CI) are propagated from the regression coefficient uncertainty only and do not incorporate climate model ensemble uncertainty or demographic change. Several important assumptions and limitations are noted. First, the dose–response is assumed linear throughout the projection period; given evidence of nonlinearity at extreme temperatures, this assumption likely underestimates future burden at the tails of warming scenarios. Second, adaptive capacity is held constant at 2023 ND-GAIN levels and no demographic change (population ageing, urbanisation) is incorporated; both are conservative assumptions that likely underestimate future DALY burden in Low adaptive-capacity countries. Third, the projection does not account for potential acclimatisation or systemic adaptation improvements over time. These design choices make the projections a conservative lower bound for heat-attributable burden under warming scenarios, and the projections should be interpreted as scenario comparisons rather than absolute forecasts.

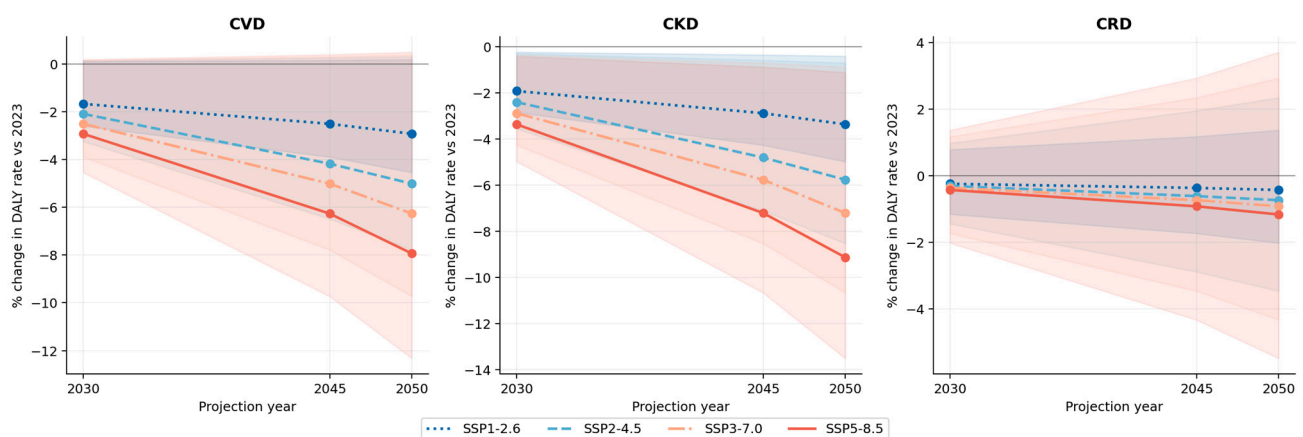


Figure 4. Projected Heat-DALY rate changes under IPCC AR6 scenarios, 2030–2050. Shaded = 95% CI.

Stratified projections reveal a severe and growing equity gap. Under SSP5-8.5, by 2050, Low adaptive-capacity countries face a projected CVD DALY rate change of -16.2% (population-weighted: -17.4%), compared with -0.7% (-10.5%) for High adaptive-capacity countries—a 23-fold unweighted disparity. The CKD burden trajectory in Medium adaptive-capacity countries is the steepest signal across all causes and strata: -17.8% (population-weighted: -19.4%) under SSP5-8.5 by 2050 (Figure 5).

The population-weighted estimates are modestly larger than the unweighted means, reflecting the concentration of large-population countries in the Low and Medium adaptive-capacity tertiles (Figure 6).

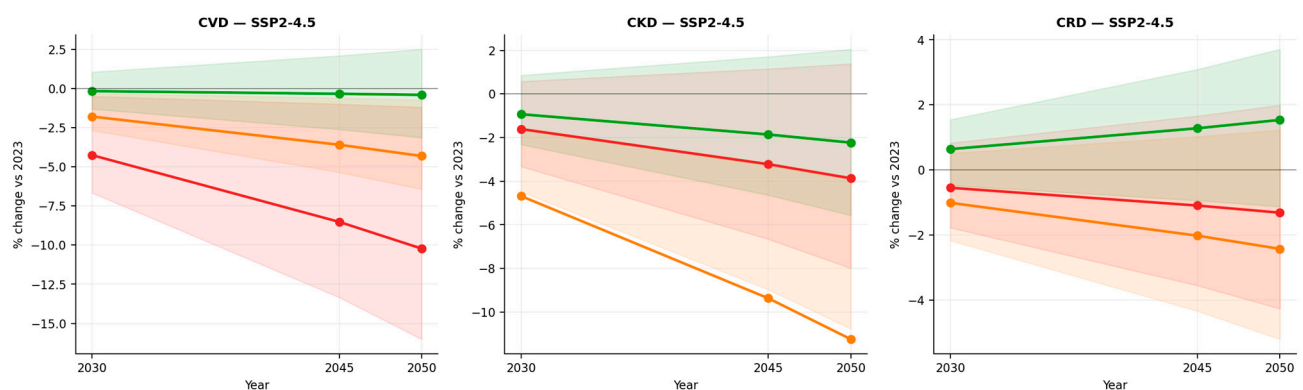


Figure 5. Cont.

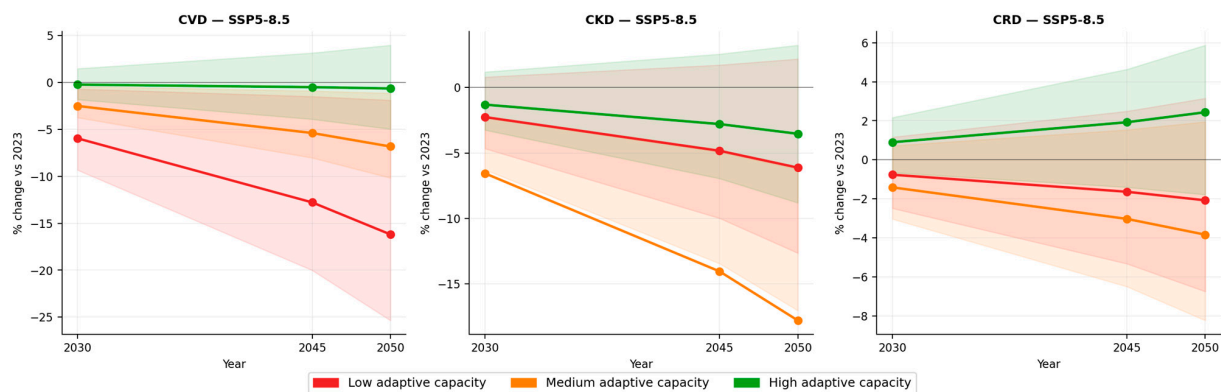


Figure 5. Tertile-stratified projections: DALY Changes under SSP2-4.5 and SSP5-8.5 (2030, 2045, 2050; shaded = 95% CI).

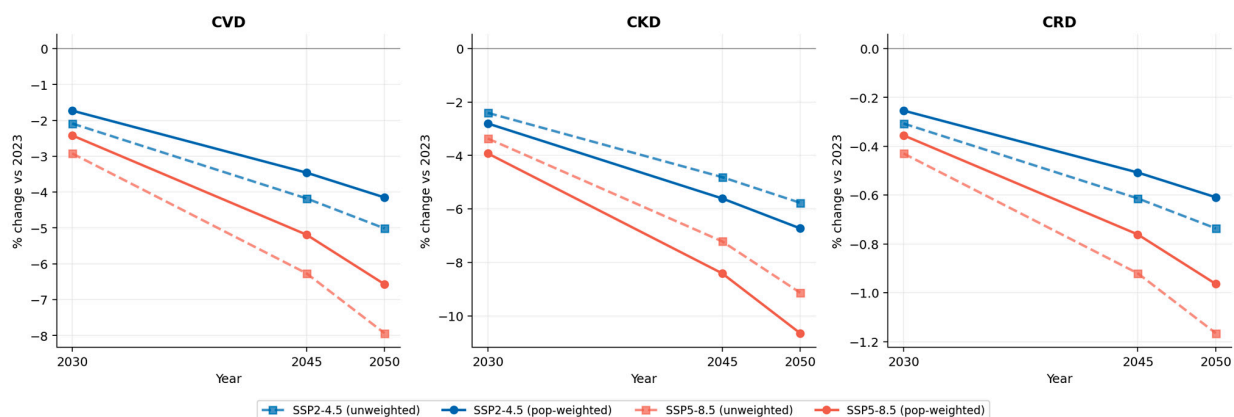


Figure 6. Population-weighted vs. unweighted projected DALY changes under SSP2-4.5 and SSP5-8.5 (2030–2050).

3.9. Benefit-of-Adaptation Counterfactual

For the 63 Low adaptive-capacity countries, upgrading to High adaptive-capacity dose–response standards would avert 9.8% of projected CVD DALY burden under SSP2-4.5 by 2050, and 15.6% under SSP5-8.5—with the benefit increasing non-linearly with warming scenario, quantifying the complementarity of mitigation and adaptation. For CKD, the Low→High upgrade averts 2.6% (SSP2-4.5) and 4.1% (SSP5-8.5) by 2050; the Low→Medium upgrade increases measured CKD burden, reflecting improved diagnostic ascertainment in higher-capacity settings rather than a genuine worsening (Figure 7).

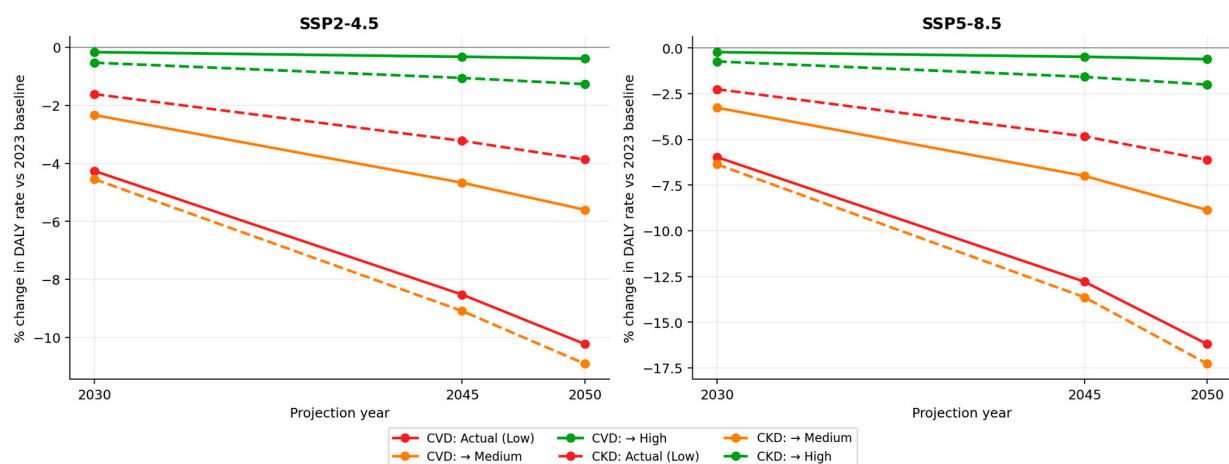


Figure 7. Benefit-of-adaptation counterfactual: Projected CVD and CKD DALY changes for Low adaptive-capacity countries under Adaptive-Capacity Upgrade Scenarios.

4. Discussion

This study provides the first formally tested, globally representative evidence that national adaptive capacity strongly and systematically moderates the heat–disease burden relationship across three cause categories simultaneously. The 26-fold disparity in heat–CVD coefficients between Low and High adaptive-capacity countries, confirmed by a statistically significant Chow test ($F = 22.0$, $p < 0.0001$), is not attributable to time-invariant country characteristics or global social trends—these are absorbed by the two-way fixed-effects specification. The finding that this gradient is robust to both contemporaneous and lagged exposure specifications and consistent with the qualitative evidence from the hi35 sensitivity analysis substantially strengthens the causal interpretation.

The CKD finding is particularly noteworthy in its policy implications. CKD DALY rates have risen 47.8% globally since 1990—against a backdrop of declining all-cause burden—and the strongest within-country heat–CKD association is in Medium adaptive-capacity countries, a category which includes the major agricultural economies of South Asia, Southeast Asia, and Latin America. This geographic and structural profile is precisely the setting where CKD of unknown aetiology (CKDu) has been documented in agricultural workers experiencing chronic occupational heat stress [6,7,14]. The attenuation of the CKD signal in Low adaptive-capacity countries almost certainly reflects diagnostic under-ascertainment rather than biological absence: the lowest-resource health systems have limited nephrology capacity, minimal CKD screening, and incomplete mortality attribution, systematically compressing the measurable DALY rate [15]. This ascertainment bias is a substantive limitation of the GBD data in low-income contexts and should be addressed in future surveillance investment.

The projection analysis extends the epidemiological findings into policy-actionable territory. The scenario divergence between SSP2-4.5 and SSP5-8.5 by 2050—from -5.0% to -7.9% for global CVD DALY change, and from -10.2% to -16.2% for Low adaptive-capacity countries specifically—quantifies the health benefits of emissions mitigation in units directly relevant to health ministers and climate negotiators. Importantly, the benefit of adaptation investment (averted DALY burden from upgrading adaptive capacity) increases non-linearly with the warming scenario: under SSP5-8.5, upgrading Low to High adaptive capacity averts 15.6% of CVD DALY burden compared to 9.8% under SSP2-4.5. This mitigation–adaptation complementarity is a finding with direct relevance to global climate finance architecture, and suggests that the health returns on adaptation investment are highest precisely when mitigation efforts are insufficient.

4.1. Positioning Within the Existing Literature

Our findings extend and formalise several streams of existing evidence. The Lancet Countdown annual reports have documented heat-related labour capacity loss, heat-related mortality trends, and adaptive-capacity indicators over time [16], but do not formally test slope heterogeneity using within-country identification. Carleton et al. [17] estimated the mortality cost of carbon using a cross-sectional income stratification approach; our TWFE design removes time-invariant confounders not accounted for in their specification, and our three-cause simultaneous framework is more comprehensive. Gasparrini et al. [18] projected temperature-related excess mortality using distributed lag models but did not incorporate adaptive capacity as a formal moderator or benefit-of-adaptation counterfactual. Bressler [19] estimated the mortality cost of carbon but used cross-national mortality data rather than DALY burden. Our study is, to our knowledge, the first to combine (i) formal within-country identification of the heat–DALY slope; (ii) a Chow test of slope equality across adaptive-capacity strata; (iii) simultaneous modelling of CVD, CKD, and CRD; (iv) GBD 2023 data; and (v) a benefit-of-adaptation counterfactual expressed in DALY units.

The planetary boundaries-based framing of this study is deliberately explicit. The observed 1.08 °C warming in our ERA5 sample between 1990 and 2023 and the projected trajectories under high-emissions scenarios correspond to progressive transgression of the climate system planetary boundary as defined by Rockström et al. [20] and updated in Richardson et al. [21]. Our findings—particularly the compounding of climate boundary transgression and adaptive-capacity deficiency in Low-income countries—provide empirical support for the hypothesis that planetary boundary breaches produce health consequences that are mediated by social and institutional buffers. The quantification of these mediating effects at the country level is a methodological contribution to the planetary health field. More specifically, this study operationalises a core proposition of the planetary health framework—that natural system disruption and social system vulnerability interact to produce health inequity—by quantifying both the biological signal (heat dose–response) and the moderating social structure (adaptive capacity) simultaneously, in a common statistical framework, and across the full global income distribution. The Lancet Countdown on Health and Climate Change [15] and the Whitmee et al. [1] Commission framing both emphasise that planetary health research must move beyond describing exposure and document the pathways by which Earth-system change translates into human suffering and death. This study contributes to that agenda by demonstrating that the same 1 °C of local warming produces a 26-fold disparity in CVD DALY slope, depending on whether a country is in the highest or lowest adaptive-capacity tertile: the biophysical force is global, but the health consequence is profoundly structured by social determinants of planetary health. The mitigation–adaptation complementarity identified in the projection counterfactual—where the health return on adaptation investment increases non-linearly as emissions rise—has direct implications for planetary health governance. It suggests that framing climate health policy as a choice between mitigation and adaptation is a false dichotomy: under the high-emissions trajectory most consistent with current policy trajectories (SSP3-7.0), the averted DALY burden from full adaptive-capacity upgrading is approximately 40% greater than under SSP2-4.5, meaning that the more planetary boundaries are transgressed, the more valuable adaptive investment becomes. This is a quantitative argument for embedding health system resilience into climate finance architecture as a core, rather than supplementary, priority—a recommendation aligned with the planetary health perspective that human health systems are themselves part of the natural–social coupled system requiring protection and reinforcement.

4.2. Limitations

Several limitations warrant careful consideration. First, the TWFE design identifies heat–DALY associations by using within-country, year-to-year temperature variation. While this controls for time-invariant confounders, it does not address time-varying confounders. Second, the ND-GAIN adaptive-capacity scores are measured at a single point in time (2023) and treated as stable across the 1990–2023 panel. Countries that have substantially improved adaptive capacity over this period may be misclassified in early years, attenuating estimated interaction effects. Third, GBD CKD DALY rates in low-income settings likely underestimate true burden due to diagnostic under-ascertainment. Finally, the projection analysis assumes a stable dose–response relationship over time, stable adaptive capacity at 2023 levels, and a linear dose–response extending beyond the historical temperature range. All three assumptions are conservative in ways that may underestimate future burden. Several additional limitations require explicit acknowledgement. Regarding TWFE and heterogeneous treatment effects: the standard TWFE estimator may conflate the upward global trend in temperature exposure with the within-country exposure effect. Although year-fixed effects partially absorb this, a true event-study or staggered difference-

in-differences design is not feasible here given the absence of a discrete treatment onset; the lagged specifications reported in Section 3.6 provide the primary robustness check. Regarding CKD ascertainment bias: the attenuation of the heat-CKD coefficient in Low adaptive-capacity countries is consistent with diagnostic under-ascertainment, but we are unable to formally quantify the magnitude of this bias from the available data. As a qualitative bound, Bikbov et al. [15] estimated that GBD CKD burden in Sub-Saharan Africa may be underestimated by up to 30–40% relative to high-income regions, due to limited nephrology capacity and incomplete cause-of-death attribution. If this order of magnitude applies here, the true Low tertile heat-CKD coefficient could be substantially larger in absolute terms than reported (−21.8, ns), potentially approaching or exceeding the Medium tertile estimate (−61.5). This would reinforce rather than weaken the policy argument for CKD surveillance investment in low-resource settings. Regarding omission bias for CRD: The null CRD association across all tertiles may reflect omission of ambient air pollution as a time-varying confounder. Air pollution (particularly PM_{2.5} and ground-level ozone) is causally linked to CRD exacerbation, co-varies with temperature within countries, and is heterogeneous across adaptive-capacity strata. Its exclusion from the model may attenuate CRD heat slopes toward zero through residual confounding, and CRD estimates should be interpreted with this caveat in mind. Regarding air pollution generally: the absence of a pollution control in the main TWFE model reflects data availability constraints for a globally harmonised annual pollution series across 187 countries over 34 years; when such data become available in future global burden analyses, pollution-adjusted models should be estimated. Regarding adaptive capacity as a static covariate: As noted in Section 2.2, using 2023 ND-GAIN scores as a time-invariant stratum is a data-driven constraint. A robustness analysis using lagged GDP per capita or historical UHC index values as time-varying proxies for adaptive capacity is recommended for future work, and would address the potential misclassification of countries that underwent substantial capacity transitions during the study period.

5. Conclusions

Adaptive capacity is not merely a correlate of heat-related health burden—it is a statistically confirmed moderator of the dose–response relationship between temperature change and DALY burden, with a 26-fold disparity in the heat–CVD slope between the least adaptive and most adaptive countries. Under high-emissions trajectories, this disparity translates into a projected 23-fold difference in CVD DALY burden change by 2050 between Low and High adaptive-capacity countries. The rising CKD burden—up 47.8% globally since 1990, concentrated in medium-income agricultural economies, and strongly heat-associated in the TWFE framework—represents an underappreciated and inadequately surveilled climate-health emergency.

These findings carry three direct policy implications. First, investments in health system adaptive capacity have quantifiable returns in averted DALY burden, with the largest marginal return in Low adaptive-capacity settings; the 15.6% CVD DALY avoidance achievable through full adaptive-capacity upgrade under SSP5-8.5 represents a concrete target for climate health financing instruments such as the Green Climate Fund and Global Fund health-systems-strengthening mechanisms. Second, the mitigation–adaptation complementarity in the counterfactual—where adaptation benefits increase non-linearly as emissions rise—provides a quantitative argument for pursuing both tracks simultaneously. Third, the CKD surveillance gap in low-income settings is not merely a data quality problem; it is a health equity problem, as populations experiencing the greatest biological heat burden may be those least likely to have it measured, treated, or counted. Viewed through the lens of planetary health, these findings reframe heat-attributable disease burden not

as an unfortunate side-effect of energy policy, but as a direct, measurable, and inequitably distributed consequence of Earth-system boundary transgression—one that is mediated by the same social and institutional structures that determine a country’s broader development trajectory. Achieving the goals of planetary health—sustaining human civilisation within the safe operating space of the planet—will require both rapid decarbonisation to slow boundary transgression and urgent investment in adaptive infrastructure to protect those most exposed to consequences of warming already locked in. This study provides a quantitative, globally comprehensive evidence base for that dual imperative.

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