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LETTER

Climate, weather, and child health: quantifying health co-benefits

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Abstract

Climate change affects human health negatively in a number of complex ways, and children are particularly vulnerable. Quantifying the negative impacts of climate change on health, and identifying locations where children are at greater risk, can aid evidence-based policy making. We combine high-resolution climatic data with a dataset on infant and child mortality, wasting, and stunting, from more than a hundred countries, to estimate the effects of both gradual and acute climate change, focusing on drought and heatwaves, to plausibly attribute changing child health outcomes to historical climate change. Our results suggest a non-linear relationship between temperature and children's health, adverse effects of increases in acute events, and a strong regional heterogeneity in these impacts. Our findings also highlight the importance of poverty reduction. Greater wealth is associated with better child health outcomes, and partially mitigates the negative impacts of climate change on child health. Finally, using updated warming scenarios, our projections show that there are substantial health co-benefits from achieving low emissions scenarios.

1. Introduction

Climate change affects human health in multiple and complex ways and these health impacts, that are in the main negative, vary across time and space, both within and across countries. Many studies provide a compelling rationale for the links between climate change and health (Watts *et al* 2019, 2020, Romanello *et al* 2021, 2022, Dasgupta and Robinson 2023). These links might be relatively direct, for example, studies have attributed increased mortality during heat waves to anthropogenic climate change (Mitchell *et al* 2016, Mitchell 2021, Philip *et al* 2021). Or they might be mediated through, for example, changes in the spread of infectious diseases (Metcalf *et al* 2017). The growing detection and attribution (D&A) literature uses formal scientific methods to identify a link between climate change and health (Ebi *et al* 2017). Single step models compare observed changes in the health variable, such as mortality, with the change that would have been expected in the absence of climate change, as proxied, for example, by temperature (Ebi *et al* 2017, Helldén *et al* 2021). A multi-step attribution model would also explicitly link the temperature increase to changes in human-caused greenhouse gas emissions.

A recent review of the literature on climate impacts on child health concludes that there is a lack of focus on how climate change is affecting the health of children in particular, with many studies only including children as a sub-population of their analysis (Helldén *et al* 2021). Further, most studies are from in high- and upper-middle-income countries or are focused on a small subset of countries (Helldén *et al* 2021, Lakhoo *et al* 2022, Phung *et al* 2023). In contrast, our paper fills an important gap by combining a large multi-country sub-national child health dataset with high-resolution climatic data to estimate robust exposure-response functions and compute impacts of future climate change on child health across lower and middle-income countries.

We quantify the links between climate change and child health at the sub-national level, focusing on mortality, malnutrition, growth retardation, stunting, and wasting, and attempt to identify and quantify relationships between climate change, weather, and child health outcomes. In the first part of this study we use a robust econometric methodology combined with sub-national level data from more than one-hundred low- and middle-income countries, to investigate the impacts of both gradual (mean temperature) and acute (drought and heatwave) climatic stressors on child health at regional and near-global scales. We find that at low temperature levels, increases in temperature are associated with lower incidences of infant mortality, child mortality, and children with stunting and wasting. However, at temperatures above a threshold, increases in temperature are associated with higher incidences. Additionally, both increasing frequency of droughts and heatwaves worsen child health and development. Along with climatic stressors, we control for socioeconomic drivers such as income and education, which allows us to incorporate societal inequality in our analysis. As such, we are able to assess health impacts to changes in both natural and social systems. Our findings are consistent across a range of robustness tests.

The rich set of socioeconomic drivers that we incorporate also differentiates our paper from epidemiological studies that use high temporal resolution (often daily) mortality data. Epidemiological studies benefit from the high frequency nature of the data, and thereby are able to capture daily and short-term variations in climatic stressors. However, they usually are not able to control for socioeconomic factors, which by their nature are collected at much lower frequency. This difference in scale has implications for policies and comparisons with epidemiological studies. Importantly, we include interactions between wealth and both long and short-term exposure to high temperature months, recognising that having higher income and wealth could reduce some of the negative impacts of climate shocks, separate from the impact of wealth of itself. Our analysis shows that frequency of heatwaves has a differentiated impact on health outcomes depending on the income and wealth of a region, with the negative impact of heatwaves declining as income and wealth increases, implying increasing inequality driven by climate change.

In the second part, we combine our econometric estimates with climate data from the sixth phase of the Coupled Model Intercomparison Project (CMIP6) to compute the impacts of future climate change on child health under various warming scenarios. This allows us to explore the health co-benefits that can be realised by achieving lower emission targets. These projections can be used to identify locations where children are at particularly high risk of the negative impacts of climate change, and for tailored policy making to tackle additional pressures that will be placed on health services. The projections show that there are substantial health co-benefits of achieving low emissions scenarios, and that only for one future scenario do the negative impacts of future climate change not fully negate the positive effects of socioeconomic development.

In the next section we detail our methodological approach, including the econometric framework that we use and the data. Section 3 details our results, which we discuss in section 4, which concludes the paper.

2. Methodology and data

2.1. Econometric framework

Following (Dasgupta *et al* 2023, Dasgupta and Robinson 2023) and the general literature on climate, weather, and socioeconomic outcomes, our paper uses a non-linear econometric approach, controlling for climate, weather, and a number of socioeconomic covariates that may act as modifiers to potential impacts of climate and weather shocks. Along with weather shocks measured by contemporaneous temperature and precipitation, we also include five-year rolling mean temperature to explore the effects of cumulative shocks on child health. We also investigate the impacts of acute events such as heatwaves and droughts. We include a number of socioeconomic variables in our analysis: income/wealth, education, and dependency ratio in the sub-national regions. The general econometric framework is shown in the equation below:

$$\ln(H_{it}) = \delta X_{it} + \theta C_{it} + \alpha_i + \gamma_t + \epsilon_{it} \qquad (1)$$

where H_{it} is one of the child health outcome for sub-national region i in year t described below (see section 2.2). Following existing literature (Pezzulo *et al* 2016, Antonelli *et al* 2020, Shayegh *et al* 2020, Shayegh and Dasgupta 2022, Dasgupta *et al* 2023, Dasgupta and Robinson 2023), δX_{it} is a vector of socioeconomic and demographic characteristics of each sub-national region, and includes the International Wealth Index (IWI), average number of years of schooling, average household size, and dependency ratio. The IWI provides a comparable asset-based wealth index. This can be used as a measure of the level of material well-being and/or standard of living of households in low and middle-income countries. We expect wealth and schooling to reduce incidences of mortality, stunting, and wasting, while dependency ratio and larger household sizes are expected to have the opposite effect. These socioeconomic and demographic drivers would reasonably be expected to negate, at least to some extent, the negative impacts on children's health of climate and weather shocks (Phalkey *et al* 2015, Vilcins *et al* 2018, Dasgupta and Robinson 2023).

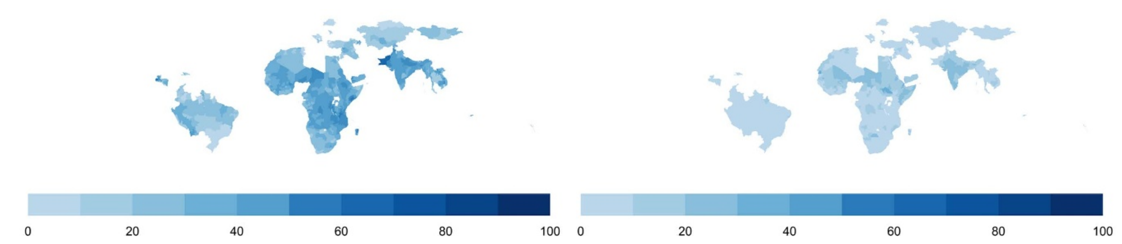

Figure 1. Average share of stunting (left-panel) and wasting (right-panel) during 1991–2018.

θC_{it} is a vector of gradual and acute climate and weather shocks, including both linear and squared terms of temperature; three and six months Standardized Precipitation Evapotranspiration Index (SPEI) as an indicator of drought that takes into account both precipitation and potential evapotranspiration in determining drought (Guttman *et al* 1994); and number of heatwave days. For heatwaves, we use the World Meteorological Organization definition, where a heatwave is defined as five or more consecutive days of prolonged heat in which the daily maximum temperature is 5 °C higher than the average maximum temperature for the period 1981–2010. Drought months are defined as those for which SPEI is below −1.5. Additionally, we include interaction terms between IWI and climatic stressors to explore the heterogeneous impact of climate change across wealth levels.

Quality of and access to healthcare along with seasonality are likely to influence child health outcomes. We control for unobserved factors such as these by including both sub-national (time-invariant unobserved heterogeneity) and year (time variant unobserved heterogeneity) fixed-effects. We use clustered standard errors at the country-level to account for correlation and heteroskedasticity among sub-national areas within a given country and to control for country-level healthcare policies.

2.2. Data

Data on child health outcomes comes from the GDL Area Database (Smits 2016) and includes development indicators at the national and sub-national level for low- and middle-income countries (LMICs) (see figure 1 for geographical coverage of stunting and wasting). This database has aggregated data from more than 600 representative household surveys such as the DHS and the MICS, and includes information at the individual and household level on socioeconomic, health, and demographic characteristics that we use to create indicators for sub-national areas (such as provinces, states, and governorates) within countries. The GDL Area Database contains a broad set of indicators (both observed and extrapolated data) for over 1300 sub-national regions from 130 LMICs for the time period 1991–2018. The full list of countries is available in appendix A1. We use only the observed health outcome data:

- Neonatal mortality: number of neonates dying before 28 days of age in the area, per 1000 live births in a given year.
- Infant mortality: number of deaths of children less than one year of age in the area, per 1000 live births in a given year.
- Under-five mortality: number of children dying under five year of age in the area, per 1000 live births in a given year.
- Wasting: percentage of children aged 0–59 months in the area below minus two standard deviations from median weight-for-age.
- Stunting: percentage of children aged 0–59 months in the area below minus two standard deviations from median weight-for-height.

The source of our historical climate data is ERA5-Land, atmospheric reanalysis of the global climate from the European Centre for Medium-Range Weather Forecasts (ECMWF). ERA5-Land combines data from global climate models with observational and satellite observations. ERA5-Land data is available at a spatial resolution of $0.1° \times 0.1°$ and hourly temporal resolution (Muñoz Sabater 2019). We start with extracting the climatic data at the native resolution, then used the LandScan population dataset (Bright *et al* 2011) available at a spatial resolution of 1×1 km to compute population-weighted climatic and weather variables aggregated at the sub-national level. We take account of two key aspects of climate change, increasing heat and heatwaves, and increasing incidence of drought, thus investigating impacts of both gradual and acute climatic stressors.

2.3. Future projections

In the second step of our analysis, we compute impacts of future climate change on child health and development by combining our econometric estimates from table 2 with SSP1-RCP1.9, SSP4-RCP3.4, SSP2-RCP4.5, and SSP3-RCP7.0 warming scenarios. We use a multi-model mean of nine

Table 1. Descriptive statistics of the main variables used in the analysis.

Variable	Mean	Std. Dev.	Min	Max
Child mortality before 28 days of age per 1000 live birth	29.32	14.35	0	93.29
Child mortality before 1 year of age per 1000 live birth	53	32.01	0	218.38
Child mortality before 5 year of age per 1000 live birth	77.99	56.31	0	373.37
Share of wasting among children	7.86	6.73	0	65
Share of stunted children	16.47	12.66	0	63.3
Mean temperature (°C)	20.8	7.01	−11.42	31.48
Drought (SPEI-6)	0.12	0.22	0	1
Average household size	6.25	1.99	2.59	20.35
International Wealth Index (IWI) score	50.36	25.1	2.7	95.31
Years of education of adults 20+	6.09	2.77	0.31	13.65

(CanESM5, CNRM-CM6-1, EC-Earth3, GISS-E2-1-G, FGOALS-g3, IPSL-CM6A-LR, MIROC6, MRI-ESM2-0, UKESM1-0-LL) Global Circulation Models (GCMs) from the sixth phase of the Coupled Model Intercomparison Project (CMIP6) climate scenarios (Eyring *et al* 2016). Using an ensemble reduces bias and model uncertainty that usually arise from using individual climate models. We use high-resolution population data (Jones and O'Neill 2016) as weights to aggregate the gridded climatic data to the sub-national level and we incorporate the projected changing pattern of future population distribution. We combine our econometric estimates to estimate child health outcomes under a baseline scenario (1995–2014), using the historical data from the GCMs, and compare these outcomes against projections for two future periods, medium-term (2031–2050) and long-term (2051–2070) (Dasgupta 2018, Hajdu and Hajdu 2021, Schleypen *et al* 2022, Dasgupta and Robinson 2023). The output is the change in child health outcomes due to future climate change compared to baseline period of 1995–2014. The description of the scenarios is available in appendix B.

3. Results

We first present key descriptive statistics in table 1 for the unbalanced panel dataset used in our analysis. Temperature, number of heatwave days, and number drought months have increased over the years, while child health outcomes have generally improved in most locations.

Consistent with existing literature (Dasgupta 2018, Carleton *et al* 2022, Dasgupta and Robinson 2023), we find a non-linear, convex relationship between temperature and all our indicators of child health: neonatal mortality, infant mortality, under-five mortality, wasting, and stunting (figure 2). Beyond certain optimal temperature thresholds, that are specific to each particular health indicator, higher temperatures are associated with worsening child health outcomes. Our findings show that these optimal temperature thresholds for health indicators range between 16.7 °C and 18.9 °C (table 2). The lowest minimum is estimated for neonatal mortality and highest for infant mortality. Countries in our database such as Iran, Lebanon, South Africa, Algeria, Syria, and Pakistan currently have mean temperatures in this range, while Tunisia, Rwanda, Zimbabwe, Malawi, Ethiopia, Uganda, and Kenya have mean temperatures that are already beyond this range.

Overall, both higher frequency of heatwave days and the number of drought months in a year are associated with worse child health outcomes across all our health indicators, with the impacts of droughts being highest for wasting. The results suggest that the most negative impact of increased frequency of heatwaves is on neonatal mortality followed by infant mortality. We do not find a statistically significant impact of increasing heatwaves on stunting.

Our findings also show explicitly that socioeconomic drivers matter for health outcomes. For example, the higher the education levels in an area, the better the child health outcomes, while larger households are linked to worse child health outcomes and development. Wealth also matters. A one unit increase in IWI reduces neonatal mortality by 0.113%. This finding is in line with the literature that concludes that economic growth improves health outcomes (Ranis *et al* 2000, Weil 2014, Dasgupta and Robinson 2023). Importantly, by including interaction terms, we show that higher levels of wealth are associated with smaller negative impacts of climate change, as manifested in increasing frequency of heatwaves, which suggests that wealth both directly and indirectly mitigates some of the negative health impacts of climate shocks. This implies in turn that climate change may be increasing inequality, but also that inequality is an important determinant of health outcomes.

3.1. Robustness tests

We run several robustness tests to validate our results. First, we replace the mean annual temperature with a five-year rolling mean temperature. The results (figure 3) are consistent with the main specification with only slight changes in the optimal temperature at which child health outcomes are

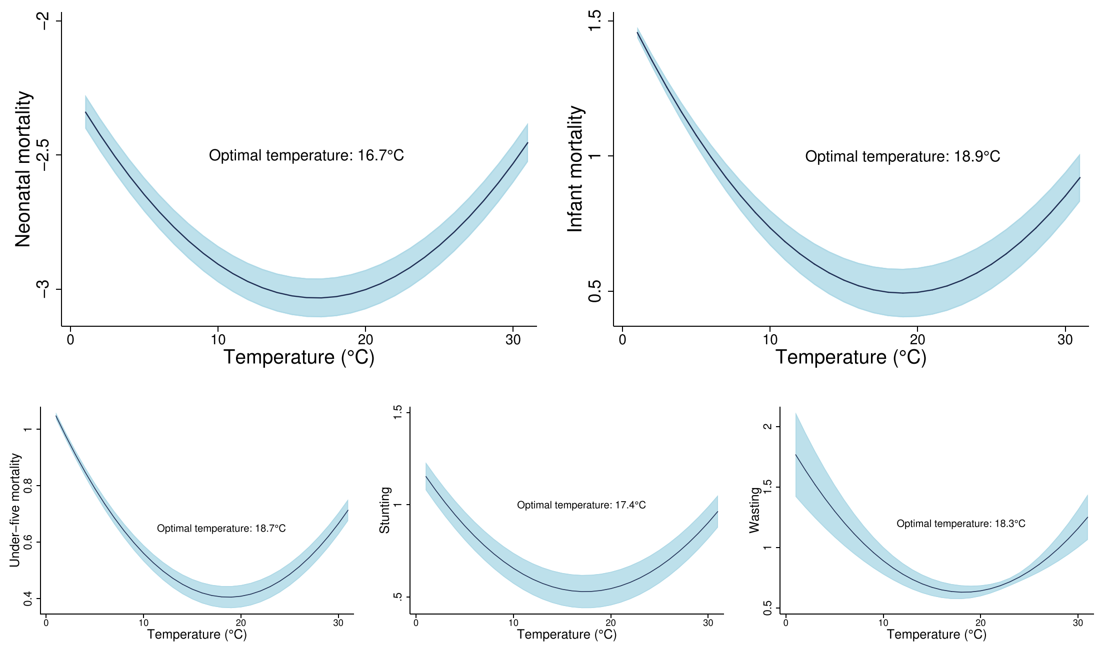

Figure 2. Optimal temperature conditions for child health outcomes.

Table 2. Main regression results.

	(1)	(2)	(3)	(4)	(5)
	Neonatal mortality	Infant mortality	<5 mortality	Stunting	Wasting
SPEI-6	0.025**	0.071**	0.071***	0.050	0.075***
	(0.039)	(0.019)	(0.004)	(0.556)	(0.000)
Mean temperature	−0.280***	−0.188***	−0.108***	−0.087**	−0.048***
	(0.000)	(0.000)	(0.000)	(0.035)	(0.000)
Mean temperature-squared	0.007***	0.005***	0.003***	0.002***	0.002***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Number of heatwave days	0.008***	0.007***	0.007***	0.001	0.006***
	(0.000)	(0.000)	(0.000)	(0.207)	(0.006)
IWI	−0.113**	−0.117***	−0.108***	−0.085***	−0.119***
	(0.042)	(0.000)	(0.000)	(0.000)	(0.000)
IWI#Number of heatwave days	−0.014***	−0.013***	−0.014**	−0.008**	−0.014**
	(0.003)	(0.002)	(0.027)	(0.009)	(0.000)
Household size	0.075***	0.001**	0.005	0.147***	0.020***
	(0.000)	(0.025)	(0.598)	(0.000)	(0.000)
Years of schooling	−0.003***	−0.004***	−0.004***	−0.013***	−0.007***
	(0.003)	(0.000)	(0.000)	(0.000)	(0.000)
Dependency ratio	0.013*	0.008	0.011***	0.017***	0.002**
	(0.087)	(0.120)	(0.006)	(0.001)	(0.041)

Robust p-values in parentheses
*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

minimised. The other coefficients are also largely similar in magnitude and statistical significance (table A2 in the appendix C).

In a second robustness test, we run a binned temperature regression with daily mean temperature into intervals of 5 °C using the 15 °C–20 °C as the reference bin. Binned regressions are semi-parametric functions that allow the capture of non-linearities. The results (table 3) suggest that additional days in the higher temperature bins result in worsening child health outcomes. These impacts are substantially higher for days in the highest temperature bins. For example, the impact of additional days in temperature greater than 30 °C bins is 1.5 times that of additional days in the 20 °C–25 °C bin. Finally, controlling for a single lag of the climatic stressors (table A3 in appendix C) instead of the contemporaneous stressors also produces similar results.

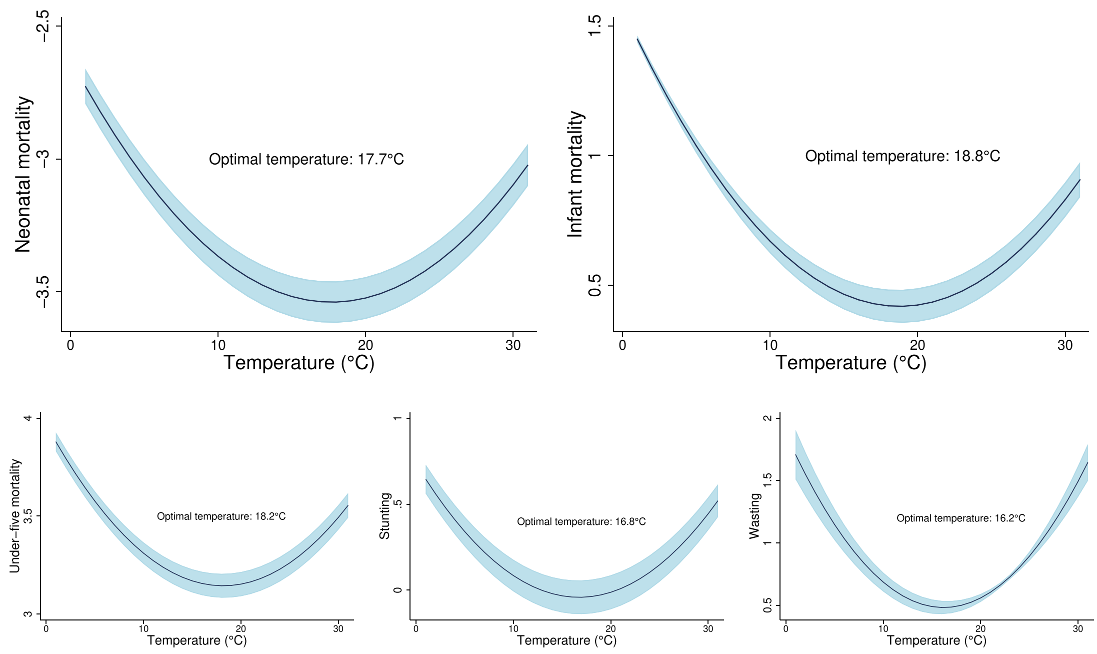

Figure 3. Optimal temperature conditions for child health outcomes—five year rolling mean.

Table 3. Regression with bins of temperature (15 °C–20 °C is the reference bin).

	(1)	(2)	(3)	(4)	(5)
	Neonatal mortality	Infant mortality	<5 mortality	Stunting	Wasting
SPEI-6	0.021**	0.062**	0.076***	0.042	0.079***
	(0.030)	(0.011)	(0.000)	(0.501)	(0.004)
<0 °C	−0.022**	−0.018**	0.019***	0.017**	0.011**
	(0.021)	(0.015)	(0.000)	(0.016)	(0.039)
0 °C–5 °C	−0.025***	−0.023***	−0.022***	−0.020***	−0.019***
	(0.000)	(0.001)	(0.008)	(0.005)	(0.007)
5 °C–10 °C	−0.030***	−0.026***	−0.025**	0.023**	0.022***
	(0.004)	(0.002)	(0.018)	(0.021)	(0.000)
10 °C–15 °C	−0.033***	−0.030***	−0.028**	−0.027**	−0.025***
	(0.000)	(0.004)	(0.010)	(0.014)	(0.001)
15 °C–20 °C					
20 °C–25 °C	0.037***	0.038***	0.035**	0.039***	0.045***
	(0.004)	(0.009)	(0.020)	(0.002)	(0.005)
25 °C–30 °C	0.045***	0.048***	0.042***	0.045***	0.051**
	(0.001)	(0.000)	(0.000)	(0.008)	(0.000)
>30 °C	0.055**	0.059***	0.050**	0.055***	0.066***
	(0.018)	(0.002)	(0.021)	(0.001)	(0.001)
Number of heatwave days	0.009***	0.008***	0.008***	0.002	0.009***
	(0.001)	(0.002)	(0.000)	(0.155)	(0.009)
IWI	−0.118**	−0.120***	−0.111***	−0.082***	−0.125***
	(0.038)	(0.001)	(0.000)	(0.002)	(0.001)
IWI#Number of heatwave days	−0.015***	−0.012***	−0.014**	−0.006**	−0.018**
	(0.003)	(0.002)	(0.027)	(0.009)	(0.000)
Household size	0.070***	0.008**	0.007	0.196***	0.028***
	(0.001)	(0.020)	(0.159)	(0.001)	(0.006)
Years of schooling	−0.005***	−0.008***	−0.007***	−0.016***	−0.004***
	(0.000)	(0.009)	(0.004)	(0.008)	(0.002)
Dependency ratio	0.018**	0.009*	0.017***	0.021***	0.004**
	(0.027)	(0.058)	(0.001)	(0.005)	(0024)

Robust p-values in parentheses
$^{***}\ p < 0.01$, $^{**}\ p < 0.05$, $^{*}\ p < 0.1$

Table 4. Percentage change in child health indicators attributed to future warming relative to the 1995–2014 baseline.

	SSP1-RCP1.9		SSP4-RCP3.4		SSP2-RCP4.5		SSP3-RCP7.0	
Scenario	2050	2070	2050	2070	2050	2070	2050	2070
Neonatal mortality	4.2	2.9	4.6	6.8	8.4	11.4	10.0	17.9
Infant mortality	5.2	3.6	6.2	8.5	9.3	12.6	11.0	16.7
Under-five mortality	2.7	2.3	2.9	4.2	4.7	6.3	5.5	9.6
Wasting share	2.0	1.0	2.3	3.2	2.6	3.7	3.3	6.3
Stunting share	2.2	1.4	2.6	3.6	3.0	4.3	3.7	7.0

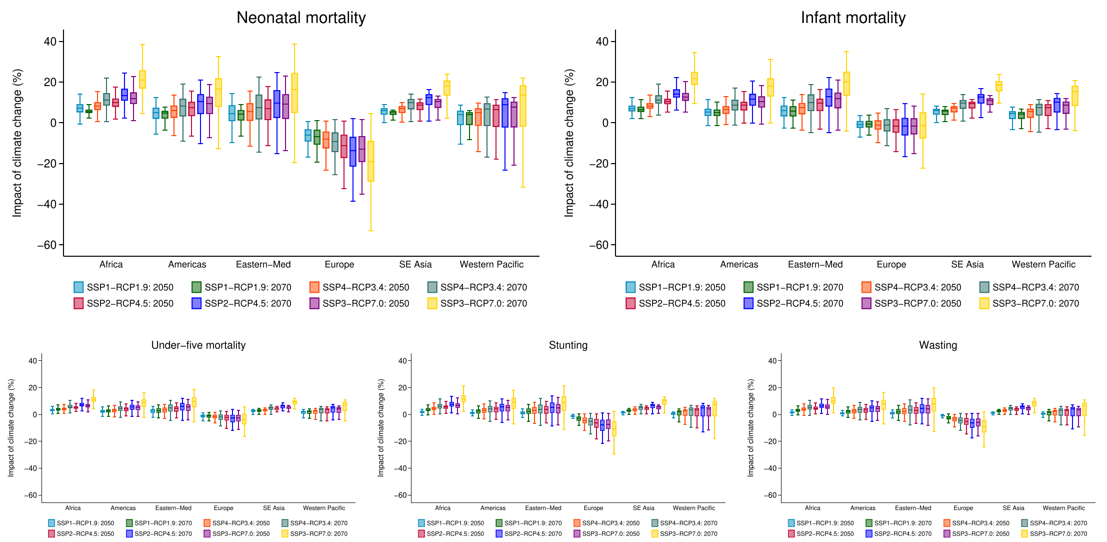

Figure 4. Impact of future climate change on child health by climate scenarios and WHO region.

3.2. Impacts of future climate change

Our projections suggest that the impact of future climate change on child health will increase over time with increasing temperatures (table 4). Future warming is projected to have the largest negative impact on neonatal mortality, the most vulnerable age group (Dasgupta and Robinson 2023). Under SSP2-RCP4.5, a middle of the road scenario, neonatal mortality is projected to increase by 4.6% by 2050 and by 6.8% by 2070; while under SSP3-RCP7.0 (considered near catastrophic) warming scenario, neonatal mortality is projected to increase by 10% and 17.9% by 2050 and 2070, respectively.

These projections clearly show the health co-benefits of mitigation strategies that achieve a low emission scenario. Due to the non-linearities in the relationship between climatic stressors and child health outcomes, child health situations are projected to be significantly worse under the higher warming scenarios. This difference is particularly striking for SSP1-RCP1.9, which reflects the Paris Agreement of achieving net zero target by 2050. Under this scenario, though climate change-induced child health outcomes are likely to worsen until 2050 compared to the reference period, in common with the other scenarios, because the rate of warming declines in the second half of the century, the share of children experiencing wasting and/or stunting, and increases in child mortality, are projected to be lower by 2070 compared to 2050 (figure 4). While not as stark, the differences between projected changes in child health outcomes under SSP4-RCP3.4 and SSP2-RCP4.5 scenarios compared to the near catastrophic SSP3-RCP7.0 are also considerable, especially in the longer term.

Only under the most optimistic climate scenario do we project that child health outcomes worsen at a lower rate between 2051 and 2070 compared to 2031 and 2050, due to warming relative to the baseline of 1995–2014. Our projections show considerable spatial heterogeneity (figures 5 and 6). For example, Saudi Arabia, Chad, Kuwait, and Burkina Faso are projected to experience the highest increases in child mortality due to climate change in the medium term, while Sudan, Ethiopia, Kenya, Niger, Mali, and Mauritania are likely to experience the highest increases in the longer term. More broadly, Africa and South East Asia are projected to experience the highest increases in child mortality, stunting, and wasting due to future climate change while these impacts are likely to be lowest in Europe (figure 4).

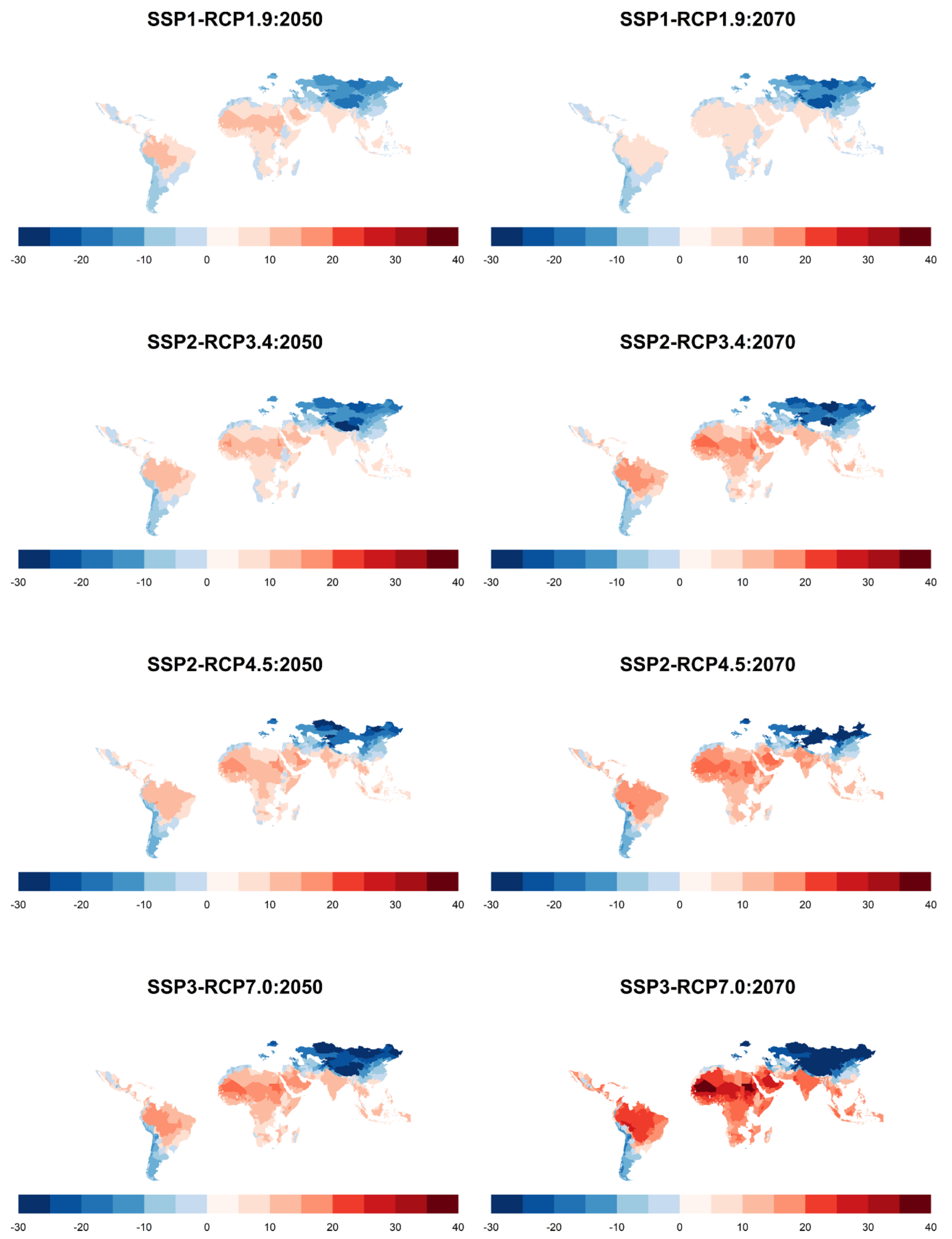

Figure 5. Neonatal mortality projections.

4. Discussion

This paper provides arguably the most comprehensive to date quantitative assessment of the impacts of climate change on child health. We demonstrate a complementary approach to the dominant detection and attribution literature (Stott *et al* 2016, Otto *et al* 2018), by estimating child health outcome-specific robust empirical relationships using sub-national level data that are consistent across a range of robustness tests. We then use these estimates to compute impacts of future climate change under various climatic and socioeconomic scenarios at second-level administrative division. These high-spatial resolution policy relevant projections can guide local-level health policies by identifying locations at highest risk of worsening child health due to climate change.

As opposed to epidemiological studies that often use daily data, we conduct our analysis using annual level data. High frequency data are particularly

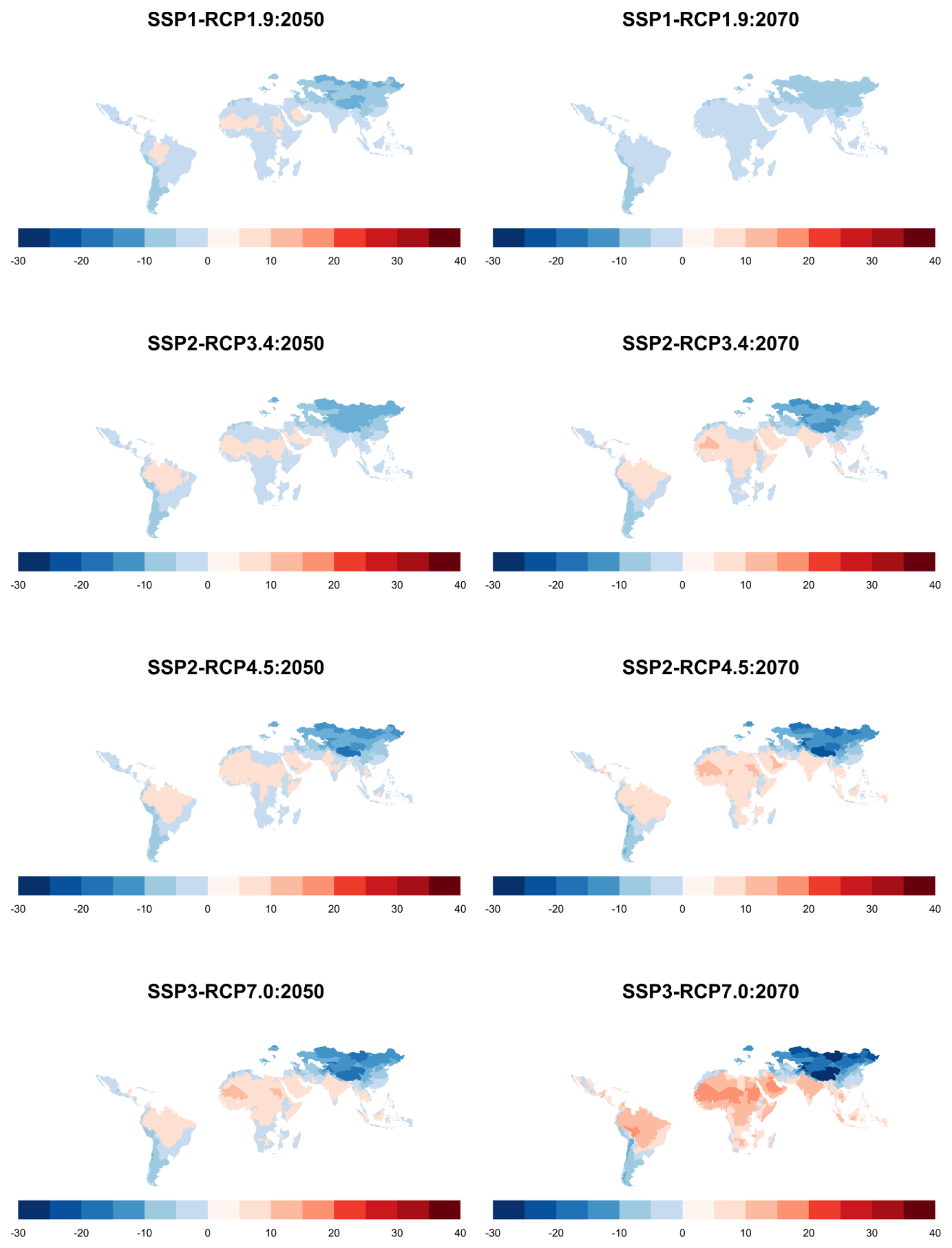

Figure 6. Wasting projections.

important when hospitalisation and mortality are the focus of a study, but not so important if longer-term conditions such as stunting and wasting are being addressed. Though we present annual data, we do incorporate seasonality in our analysis, and indeed our results highlight the importance of addressing seasonality explicitly. For example, we find that short and medium term seasonal drought shocks, as measured by SPEI-12, have the largest impact on wasting, which is considered an indicator of acute rather than chronic malnutrition. Our analysis is not without limitations. For example, due to lack of data we are not able to control for conflicts, which, because they are likely to have a negative affect on health outcomes, could bias our estimates downwards.

While our analysis is not able to control for daily variations in climatic stressors, we are able to control for a rich set of socioeconomic drivers that significantly affect child health and development more broadly. This is important, because in low and middle-income countries, improvements in health, education, water and sanitation, and female empowerment, amongst other factors, are essential if these countries are going to reduce poverty and increase prosperity (OECD 2003, Duflo 2012, WHO and UNICEF 2021). Yet climate change is making this ever more difficult. Moreover, given that causality between health and income tends to be bi-directional (Weil 2014), countries could at the extreme find themselves in a vicious circle of poverty and poor health with the impacts of climate change on health outweighing development efforts to increase economic growth and reduce poverty and in parallel improve health.

The environmental epidemiological literature has not focused on interactions between socioeconomic and climatic stressors. In contrast, our empirical results underpin the importance of taking explicit account of socioeconomic drivers and interaction terms. For example, one particular novelty of our work is that we find heatwaves have differentiated impacts on child health and development across wealth levels. Specifically, greater wealth partially negates the negative impacts of heatwaves. With climate change expected to result in declining income (Kotz *et al* 2024) and increasing inequality (Dasgupta *et al* 2023), the heterogeneity in health impacts of climate change across wealth and income settings are also likely to increase.

Our results are consistent with literature that finds, for example, that drought conditions are associated with both stunting and wasting (Lieber *et al* 2022), and that extreme heat is linked to a broad range of negative health outcomes (Mitchell *et al* 2016, Mitchell 2021, Philip *et al* 2021, Dasgupta and Robinson 2023). We also confirm the importance of socioeconomic determinants of health, including wealth and parents' education levels, which highlights the importance of economic growth in lower-income countries as essential both to meet the sustainable development goals and to build resilience to the changing climate. Moreover, the non-linear relationship between wealth and climate impacts, and spatial heterogeneity, highlights the importance of understanding both the impact of inequality on health outcomes, and the impact of health outcomes on inequality.

The methodology underpinning our projections differs from that found in the dominant literature. Specifically, we only compute projections using the most updated climate change scenarios for the regions for which we have observed child health outcomes data. A common weakness in the climate impacts literature is the use of response-functions based on observed data from just a few locations to compute projections for the whole world.

Our projections under various future climate change scenarios show the child health co-benefits that can be achieved under low-emission scenarios compared to the high-emission ones. These co-benefits are particularly substantial under the Paris agreement compatible scenario of SSP1-RCP1.9. Moreover, because the health of people in lower-income countries tend to be most harmed by climate change, the health co-benefits from more rapid emissions reductions are likely to be greatest in these countries.

In taking this approach, our paper is able to calculate clear and plausible quantified health co-benefits from global efforts to tackle climate change, recognising that both mitigation and adaptation will be needed for decades to come. Individual countries have scope to contribute to global emissions reductions consistent with their nationally determined contributions, whilst also reaping the local level health co-benefits of their actions, which also contributes to adaptation. Three clear areas are reducing air pollution, improved diets, and more active lifestyles. Each of these approaches has clear health co-benefits for local populations, that can be implemented and measured at the local or national level. Future research could examine the health co-benefits local-level mitigation approaches and strategies using country deep-dive approaches.

Our results also makes clear that lower-income countries will find it increasingly difficult to achieve the sustainable development goals given the impact of the changing climate on health outcomes. Indeed, climate change is negating many of the investments that LMICs have made in child and maternal health, and putting increased pressure on health services. However, it is possible to end on a note of optimism. Our projections, in common with the literature, assume no adaptation. That is, they do not predict the future, but rather highlight the tremendous potential health co-benefits from both mitigation and adaptation.

Data availability statement

The data cannot be made publicly available upon publication due to legal restrictions preventing unrestricted public distribution. The data that support the findings of this study are available upon reasonable request from the authors.

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