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Supplemental files.docx	Supplementary Material for Review	67.0 KB	Page 82
Response to referees.docx	Author Response	57.6 KB	Page 84

Running Head: HEAT AND EARLY CHILDHOOD DEVELOPMENT

Ambient Heat and Early Childhood Development: A Cross-National Analysis

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Abstract

Background: Increasing evidence suggests that climate change, along with its cascading impacts on ecosystems, societies, and communities, has significant effects on both physical and mental health. However, less is known about how exposure to excessive heat early in life may influence the development of foundational skills that shape lifelong developmental trajectories. This study examined the effects of ambient heat on early childhood development across six countries, using geographic and time-stamped data on child development and ambient temperature. **Methods:** Our primary outcome is the Early Childhood Development Index (ECDI). We used linear probability models with geographic and seasonality fixed effects to account for baseline climatic conditions, as well as other individual and contextual covariates to address potential selection bias. The sample comprised 19,607 children aged three and four from Georgia, The Gambia, Madagascar, Malawi, Sierra Leone, and The State of Palestine, all participants in Multiple Indicators Cluster Surveys collected between 2017 and 2020. We merged these data with temperature data from the ERA5-Land Monthly Aggregated Climate Dataset, calculating the mean monthly maximum temperature children experienced from birth to interview. **Results:** We found that children exposed to average maximum temperatures above 32°C were less likely to be developmentally on track compared to those exposed to cooler temperatures, even after accounting for baseline average climatic conditions and other covariates. Domain-specific models indicate that these effects were most pronounced in literacy and numeracy skills. Subgroup analyses revealed that the negative impacts were particularly severe for children in economically disadvantaged households, urban areas, and for those lacking access to adequate water and sanitation. **Conclusions:** This study highlights the potential impact of excessive heat on early childhood development, emphasizing the need for policies and interventions that enhance preparedness, adaptation, and resilience to support human development in an increasingly warming world.

Keywords: Heat exposure, early childhood development, climate change, temperature

Abbreviations:

ECDI: Early Childhood Development Index

MICS: Multiple Indicators Cluster Survey

Statement of Relevance

The world recorded unprecedented temperatures in 2024, and a warming planet poses significant risks to both human development and health. While much is known about the broader impacts of climate change, less attention has been given to how high temperatures affect young children's development. Our study explored the effects of ambient heat on key developmental domains—literacy-numeracy, physical health, social-emotional well-being, and approaches to learning—across six countries: Georgia, The Gambia, Madagascar, Malawi, Sierra Leone, and The State of Palestine. We found that children exposed to average maximum temperatures above 32°C were less likely to be developmentally on track compared to those exposed to cooler temperatures. Moreover, these negative effects were most pronounced for children from economically disadvantaged backgrounds, those living in rural areas, and those lacking access to clean water and adequate sanitation. These findings underscore the urgent need for policies and interventions to protect human development in an increasingly warmer world.

Ambient Heat and Early Childhood Development: A Cross-National Analysis

Climate change is profoundly changing the ecology of human development. The year 2024 has been the warmest one on record, exceeding for the first time the 1.5° above pre-industrial levels for the annual average temperature set as a benchmark in the Paris Agreement (Romanello et al., 2024). Climate change can increase the risk for severe storms, atypical precipitation patterns, loss of biodiversity, ocean acidification, increased pollution, and food and water scarcity, which altogether can in turn affect human societies and communities (Pörtner et al., 2022).

A warmer earth, and its cascading effects on the physical environment, societies, and communities, can undermine human health, learning, and wellbeing. Meta-analyses indicate that exposure to excessive ambient heat is associated with an increased risk for multiple physical and mental health problems in childhood and adulthood (Blom et al., 2022; Thompson et al., 2023; Weeda et al., 2024). Excessive heat can also inhibit children's and adolescents' learning and achievement in standardized tests (Park et al., 2021; Prentice et al., 2024). Moreover, hotter temperatures have been linked to an increased risk of interpersonal violence, including violence against children and gender-based violence (Evans et al., 2025; Mahendran et al., 2021).

However, there is little evidence on how exposure to excessive ambient heat early in life, which is a sensitive period of brain development, may affect the development of foundational skills (Black et al., 2017; Cuartas et al., 2024; Draper et al., 2024; Herbst, 2024). High ambient temperatures may affect early childhood development by causing dehydration, neuroinflammation, heightened activation of the stress response system, and disrupted sleep (Berger et al., 2023; Sorensen & Hess, 2022; Walter & Carraretto, 2016; White et al., 2007; Yan et al., 2023). Young children are particularly vulnerable to ambient temperatures given their heightened sensitivity to environmental input, their under-developed biological systems, which are less capable of regulating and releasing heat via sweating, and their dependence on adults to seek water or cooler environments (Early Childhood Scientific Council on Equity and the Environment, 2023).

Excessive ambient heat can also influence young children's development through broader ecological mechanisms. For example, extreme heat can damage crops, increase the risk of food contamination, and promote the spread of disease vectors such as mosquitoes, all of which threaten children's health and nutrition, essential foundations for healthy development (Draper et al., 2024; Kemp et al., 2022; Schlenker & Roberts, 2009). Additionally, the well-documented effects of heat on mental health may impair parenting and reduce the quality of caregiver–child interactions, both of which are critical for the development of cognitive and socio-emotional skills (Bornstein, 2015; Cuartas et al., 2024). Excessive heat may also limit children's exposure to learning opportunities by making outdoor environments less safe and contributing to more sedentary behavior (Koepp et al., 2023). Consequently, understanding the developmental effects of early exposure to heat remains critical, especially considering that over one third of children around the world are highly exposed to heatwaves and almost every child on earth is already experiencing the downstream consequences of climate change (Rees, 2021).

Understanding the developmental consequences of exposure to excessive ambient heat is challenging due to issues of selection bias (Bailey et al., 2024). Specifically, individuals with certain characteristics "self-select" to live in different settings, and some of these characteristics may predict developmental outcomes, confounding the estimated effects. Similarly, comparing children living in hot and cold regions is not informative to isolate the effects of heat on child development, as hot and cold regions may differ in factors other than temperature (e.g., ecosystemic, economic, and social) that also influence development. Multiple confounders are difficult (if not impossible) to measure and hence unobserved by researchers, exacerbating selection bias issues.

This study addresses these gaps in the literature by studying the effects of excessive ambient heat during early childhood on early childhood development skills in six countries. Following work in environmental economics (e.g., Deschenes, 2014), we mitigate concerns about selection bias by linking geocoded data on children with high-resolution longitudinal temperature data. Specifically, our approach allows for comparisons among children living within the same subnational region, thereby reducing concerns about systematic differences in climatic, economic, or social conditions across regions, while also accounting for seasonality effects.

Furthermore, we examined whether the effects of ambient heat on child development varied between wealth groups, urban versus rural settings, and household with and without access to adequate water and sanitation. These factors were selected as potential moderators because they may either mitigate or exacerbate the risks associated with excessive heat (Balza et al., 2025; Romanello et al., 2024) – for example, by providing resources to cope with heat (such as access to clean water) or by amplifying exposure and related risks (such as increased heat concentration in urban areas – known as the urban heat island effect – or contamination in households lacking adequate sanitation). Finally, given the unequal distribution of vulnerability to and gender-differentiated impact of different climate hazards (Awiti, 2022), we conducted an exploratory analysis to assess whether the effects of ambient heat differed between boys and girls.

Open Practices Statement

This study followed the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) reporting guidelines. The analyses presented in this article were not formally preregistered. Neither the data nor the materials have been archived in a permanent third-party repository. The MICS and climate data used in this study are publicly available. Geocoded information from the MICS can be obtained upon request from the survey developers (mics.unicef.org).

Methods

Sample & Procedures

We spatially combined data from the MICS and the ERA5-Land Monthly Aggregated Climate Dataset. Developed by UNICEF (2005), The MICS are nationally representative household surveys that employ stratified, multistage cluster sampling approaches and aim to collect internationally comparable data on children and women. Households are selected using probability proportional to size sampling within clusters, which correspond to the primary sampling units and typically include 20-25 geographically proximate households, often within a single census enumeration area. In this study, we used data from six countries included in the sixth round of the MICS: Georgia (2018), The Gambia (2018), the State of Palestine (2019–20), Madagascar (2018), Malawi (2019–20), and Sierra Leone (2017). We selected these countries because they were the only ones with available data on both geolocated household clusters, that is, geographic coordinates for each cluster, and child development, as measured by the Early Childhood Development Index (ECDI). These clusters serve as the primary units of analysis for spatial linkage with climate data.

Climate data were sourced from the ERA5-Land Monthly Aggregated Climate Dataset, produced by the European Centre for Medium-Range Weather Forecasts (Hersbach et al., 2020). This dataset combines satellite observations, in-situ measurements, and numerical weather prediction models to generate consistent, continuous, and high-resolution climate records at a spatial resolution of approximately 9 kilometers (0.1 degrees). The data includes hourly information on surface variables, including data on temperature and precipitation, from 1950 to approximately two months before the present. We overlaid the geolocated MICS clusters with the ERA5-Land climate grids in Google Earth Engine (see Figure 1). We conducted a complete case analysis, and the analytic sample for this study included 19,607 children aged three and four years in 3,646 unique clusters. Table 1 presents descriptive statistics of this sample.

[FIGURE 1]

[TABLE 1]

Measures

Child Development. We used the Early Childhood Development Index (ECDI; Loizillon et al., 2017) to assess children's early development. The ECDI is a 10-item parent-reported scale that measures basic developmental milestones between the ages of 36 to 59 months in four domains: social-emotional, literacy-numeracy, approaches to learning, and physical. The ECDI is highly policy relevant because it is a proxy indicator for the Sustainable Development Goals Indicator 4.2.1 and one of the few comparable measures of child development widely used in large-scales surveys across countries. We computed a sum index of the 10-items and then characterize children to be developmentally "on-track" if they exhibited at least 50% of each domain's relevant skills, following the developer's guidelines (Loizillon et al., 2017). In the analytic sample, almost 63% of children were developmentally on track and 37% not on track according to the ECDI.

Heat Exposure. We leveraged the geographic coordinates collected by the MICS and exact data on children's birthdates and survey interview dates to establish heat exposure. After overlaying the MICS and ERA5 data spatially, we applied a buffer of 5 kilometers around each MICS cluster point. The buffer accounts for local climate variability and random displacement of clusters, up to 2 km in urban areas and 5–10 km in rural areas, carried out by the MICS to ensure respondents' privacy. Within these buffers, we followed related literature (Aguilar-Gomez et al., 2024; Deschenes, 2014) and extracted and averaged the climate variables for each buffer by month for each child, specifically calculating the mean monthly maximum temperature that children were exposed to from birth to the interview date. Due to the absence of residential history data in MICS, we assign temperature exposure based on the child's current cluster of residence, implicitly assuming residential stability from birth through the time of the survey. Figure 2 presents the distribution of maximum temperature by country for the analytic sample.

[FIGURE 2]

Covariates. Our analysis included a set of child, caregiver, household, and contextual characteristics as covariates. The MICS data provided information on children's sex and age in months, maternal education (none, primary, secondary, or more); household wealth quintiles, as measured by a composite index of dwelling characteristics and household assets; and an indicator for urban versus rural areas. We also extracted a composite measure for dew point temperature, which is an absolute measure of atmospheric moisture, and surface pressure from the ERA5-Land as an additional atmospheric covariate. Our data also included information on children's exact birthdates, interview dates, and subnational regions (within countries) where clusters were located. Finally, we computed indicators for households' access (or lack thereof) to improved water and sanitation to assess potential heterogeneous effects of heat according to access to these basic services, following guidelines by the World Health Organization (2019)

Analytic Approach

We used the linear probability model presented in Equation 1 to estimate the relation between heat exposure and child development. In this model, Y_{igt} represented the outcome variable for child i in geographic area g and date t. The model also included binary indicators for each degree Celsius, using exposure to average maximum temperatures below 26°C as the reference category (i.e., temperature bins). This threshold was informed by evidence suggesting potential adverse effects of temperatures above 26°C on mental health and behavior (Evans, 2019; Thompson et al., 2023) as well as the temperature distribution in the current sample. In this specification, $Tmax_{igt}$ represented the mean maximum temperature bins. A binned specification is common in the related literature and allowed us to account for potential non-linear associations between heat and child development (Aguilar-Gomez et al., 2024; Deschenes, 2014).

$$Y_{igt} = \sum_{b=1}^{x} \beta_j Tmax_{igt} + \sigma \boldsymbol{X}_i + \gamma_g + \rho_t + \epsilon_{igt} \tag{1}$$

In the model, $\boldsymbol{X}_i$ was a set of covariates (children's age and sex, maternal education, wealth quartiles, area, dew point temperature and surface pressure, and child birthdate), and γ_g and ρ_t denoted subnational region-country fixed effects and month-year fixed effects, respectively. These fixed effects allowed us to control for seasonality effects and restrict comparisons between children within the same country and same subnational region who were exposed to different average maximum temperatures due to temporal variation in temperature levels relative to their birthdates and interview dates. Causal identification thus assumed that after controlling for baseline average climatic conditions (by including geographic and seasonality fixed effects), any residual fluctuations in temperature was unexpected or exogenous.

Furthermore, we estimated additional models using the indicators for being developmentally on track for each ECDI domain as outcome variable to assess whether effects on a particular domain may drive the observed associations with the overall ECDI. We also conducted two sensitivity analyses to test the robustness of the results. First, although the selection of 26°C as the reference category in our binned specification was informed by prior evidence, we also conducted a data-driven binscatter least squares estimation as a sensitivity check. In this approach, the continuous temperature variable is divided into intervals (or bins), and each point in the plot represents the average ECDI score within a temperature bin, plotted against the average temperature in that bin, allowing us to visualize the underlying functional relationship while smoothing out noise. Second, we estimated probit and logistic regression models instead of linear probability models, which account for the bounded nature of binary outcomes and allow for nonlinear relationships between the predictors and the probability of the outcome, providing a useful check on whether our findings are sensitive to the functional form of the model and distributional assumptions.

Finally, we assessed potential moderating effects or heterogeneity in the observed associations by estimating independent effects for different subgroups, including: (1) wealth below and above the median, (2) urban versus rural, and (3) those with and without access to both improved water and improved sanitation. These analyses are helpful to understand the potential risk factors that may compound the effects of heat on early child development.

Results

Estimates of the Effects of Heat on Early Child Development

Figure 3 summarizes results from our primary linear probability regression analysis estimating the association between temperature bins and being developmentally on track according to the ECDI. The Figure presents predicted margins (i.e., model-based predicted probabilities of the outcome at specific values of the independent variable) for the unadjusted model which does not include any covariates, and for the model including all covariates and geographic and temporal fixed effects. The unadjusted estimates show a clear gradient, with children experiencing hotter average temperatures having a lower likelihood of being developmentally on track. For example, children who were exposed to an average maximum temperature of more than 30°C were between 14 (SE=0.019) and 20.8 (SE=0.018) percentage points less likely to be developmentally on track compared to those who were exposed to average maximum temperatures experienced lower than 26°C. The adjusted model, including all covariates and our preferred model, showed that some, but not all, of these associations may be due to confounding. Specifically, it showed that children who were exposed to an average maximum temperature of 32°C were between 1.8 (SE=0.033) and 7.7 (SE=0.039) percentage points less likely to be developmentally on track compared to those who were exposed to average maximum temperatures lower than 26°C, with some bins not reaching statistical significance but being consistent in directionality. In general, both models showed the same drop in the probability of children being on track after exposure to average maximum temperatures higher than 30°C–31°C.

[FIGURE 3]

Table 2 presents results for the ECDI domain-specific analysis. Children who were exposed to monthly average maximum temperatures above 30°C had lower probabilities of being developmentally on track in the literacy-numeracy domain, with a statistically significant association ranging between 5 (SE=0.025) and 6.7 (SE=0.032) percentage points, relative to those who were exposed to average maximum temperatures lower than 26°C. We also observed a statistically significant association between temperatures of 32°C and a 6.9 (SE=0.034) percentage points lower likelihood of being developmentally on track in the socio-emotional domain, relative to temperatures below 26°C. Similarly, temperatures of 26°C are associated with a 2.2 (SE=0.013) percentage point higher likelihood of being on track in the physical domain relative to temperatures below 26°C.

[TABLE 2]

Figure 4 presents estimates from an alternative data-driven binscatter least squares estimation using continuous ECDI total scores and including all control variables and geographic and temporal fixed-effects. The results were consistent with findings from our main specification, showing a negative association between ambient temperature and ECDI scores after accounting for baseline average climatic conditions and other individual and contextual covariates. Moreover, the predicted margins estimated using the probit and logit models were consistent with those from the linear probability model (see supplemental files, Figure S1).

[FIGURE 4]

Finally, while the main goal of this study was to assess the potential effects of excessive heat exposure from birth to the MICS interview date, extensive evidence also indicates that in-utero exposure to excessive heat can negatively impact human development outcomes (Brink et al., 2024). Consequently, we conducted a sensitivity analysis to examine the association between prenatal exposure to excessive heat and being developmentally on track (ECDI), assuming an average pregnancy duration of nine months. Our results, presented in Table S2 (supplemental files), show somewhat inconsistent association between temperature bins and the ECDI. We observed statistically significant associations between temperatures of 26°C and 27°C in the first trimester of pregnancy and a 4.1 (SE=0.020) and 3.3 (SE=0.018) percentage points higher likelihood of being developmentally on track, as well as between temperatures of 33°C and a 3.5 percentage points (SE=0.020) lower probability of ECDI on-track, relative to temperatures below 26°C. Moreover, temperatures of 34°C in the third trimester were associated to a 4.2 lower likelihood (SE=0.020) of being developmentally on track relative to temperatures below 26°C. These results align with recent evidence on how heat can exacerbate risks for neurodevelopment early and late in pregnancy (Lin et al., 2025).

Heterogeneity in the Effects of Heat Exposure on Early Child Development

Subgroup analyses revealed pronounced heterogeneity in the association between heat exposure and early childhood development (Figure 5). Children from economically disadvantaged households appear to bear a disproportionately higher burden. For example, children below the median experienced a reduced likelihood of being developmentally on track as temperatures increased, whereas this trend is not evident for those at the top of the wealth distribution. In addition, area-based differences emerge, with children exposed to high ambient temperatures and living in urban areas experiencing between 21.9 (SE=0.091) and 26.6 (SE=0.087) percentage points reductions in the likelihood of being developmentally on track, whereas those in rural areas did not experience such effects. Finally, children in households lacking improved water sources experienced stronger reductions in their likelihood of being developmentally on track when exposed to high heat (up to 13.9 percentage points, SE=0.082).

[FIGURE 5]

Discussion

Climate projections suggest that current actions (and inactions) by governments and societies could lead to a temperature increase of 2.1°C to 3.9°C above pre-industrial levels (Climate Action Tracker, 2024; Kemp et al., 2022). A warmer world may trigger cascading effects, including rising sea levels, more frequent extreme weather events, the spread of vector-borne diseases, loss of ecosystem services, forced displacement, macroeconomic instability, conflict, resource shortages, and negative impacts on both physical and mental health (Kemp et al., 2022; Romanello et al., 2024). Despite the widespread recognition of these risks, including advocacy and discussion pieces highlighting the dangers of excessive heat for children (Early Childhood Scientific Council on Equity and the Environment, 2023; Rees, 2021), research linking ambient heat to early childhood development remains limited. This study leveraged novel spatial and temporal data to examine how excessive heat may impact the development of foundational skills in young children across six countries that vary in terms of socioeconomic characteristics, culture, and climatic conditions.

We found that children exposed to monthly average maximum temperatures above 30°C were less likely to be developmentally on track compared to those exposed to cooler temperatures. This association was consistent even after controlling for baseline average climatic conditions, by comparing children in the same subnational region and adjusting for seasonality effects, as well as other individual and contextual factors. These findings align with literature across multiple disciplines highlighting the environmental, health, and behavioral risks that high temperatures pose to early child development. For example, warm temperatures tend to accelerate the proliferation of disease vectors and bacteria that cause gastrointestinal and respiratory illnesses (Kemp et al., 2022). Similarly, crop yields are adversely affected at temperatures above 34°C, and warmer conditions also heighten the risk of food contamination, which in turn threatens children's health and nutrition and therefore development (Schlenker & Roberts, 2009). For example, one study estimated that a 2°C temperature increase could lead to a 7.4 percentage point rise in stunting, while temperatures exceeding 30°C are associated with a 2.2 percentage point increase in wasting rates (Blom et al., 2022). Finally, temperatures above 26°C can also increase adults' mental health conditions, aggression, and interpersonal violence, with potential downstream effects on children's safety and development (Evans, 2019; Thompson et al., 2023).

Domain-specific analyses suggest that the impact of heat on early child development may be particularly driven by its effects on cognitive literacy-numeracy skills, which aligns with prior research showing the adverse effects of heat on cognition. For example, temperatures above 32°C have been linked to a nearly 10% reduction in adult cognitive function and accelerated cognitive decline in the adult population (Choi et al., 2023; Yin et al., 2024). Similarly, temperatures above 26.7°C can impair cognitive performance in children and adolescents (Park, 2022; Park et al., 2021). Excessive heat can impact cognitive development directly (Piil et al.,

2020) and indirectly through several mechanisms, including dehydration, increased activation of the stress response system, neuroinflammation, damage to nerve cells due to inadequate heat dissipation, and disrupted sleep (Berger et al., 2023; Sorensen & Hess, 2022; Walter & Carraretto, 2016; White et al., 2007; Yan et al., 2023). Similarly, it can reduce children's physical activity, increase sedentary behavior, and reduce opportunities for interaction with others outside the home (Koepp et al., 2023).

Conceptually, the same mechanisms linking excessive heat with cognitive outcomes could also affect children's physical and social-emotional development. However, in our sample, the evidence for such associations was less consistent. We found a statistically significant association between temperatures of 32 °C and a lower likelihood of being developmentally on track in the socio-emotional domain, but not at higher temperatures. This inconsistent pattern may reflect measurement limitations in socio-emotional development relative to the literacy-numeracy domain, as noted in prior research (McCoy et al., 2016). Similarly, we observed a positive association between temperatures of 26 °C and physical development, relative to cooler days, but again no consistent effects at higher temperatures. These mixed findings suggest caution in interpreting the effects of heat on physical and socio-emotional development in this sample. It is also possible that the effects of early-life heat exposure emerge more clearly in cognitive outcomes during early childhood, with impacts on other domains, such as socio-emotional functioning becoming evident only later in life. Future studies using more precise measures and longitudinal designs are needed to clarify these patterns.

We also found that the effect of high temperatures on early child development is heterogeneous, with particularly severe effects on children from economically disadvantaged households, urban areas, and households with limited access to essential services. Families from economically disadvantaged backgrounds and in urban areas are more likely to live in housing and areas that trap heat and are less likely to have access to air conditioning, public cooling spaces, and clean drinking water, which increases the risk for heat stress and children's exposure to heat-related hazards (El Khayat et al., 2022; Gronlund, 2014). Furthermore, combined with inadequate access to water, which was found to be a significant moderator, heat exacerbates the risks of water scarcity, contamination, and disease transmission. Exposure to pollutants and contamination during early childhood can disrupt synapse development in key brain areas, thereby impairing children's cognitive and social-emotional developments (Walker et al., 2011). Conversely, access to adequate water can act as a protective buffer against the detrimental effects of heat on children by offering a readily available means of cooling (Balza et al., 2025).

Findings from the heterogeneity analyses highlight the urgent need to prioritize support for economically disadvantaged communities in efforts to mitigate heat-related risks to early childhood development. A critical area of investment, as suggested by the current results, is the provision of reliable water and sanitation infrastructure, which can offer opportunities for cooling and reduce exposure to heat-related contaminants. Additional support may include cash transfer programs, which can enhance families' ability to access resources needed to cope with extreme heat, and the distribution of cooling tools, such as fans. Furthermore, the finding that heat effects are more pronounced in urban compared to rural areas, consistent with the urban heat island effect, underscores the importance of ecological and infrastructure-based interventions, including increasing vegetation cover, implementing cool surface technologies, and enhancing urban infrastructure to support temperature regulation.

Limitations

This study makes significant contributions to the literature on the developmental consequences of excessive ambient heat, but it also has limitations. First, although we accounted for baseline average climatic conditions and other potential confounders, there may still be unobserved factors that could have biased the results. Additionally, while we can accurately assign temperature levels to children who remained in the same cluster throughout their lives, this is not possible for those who migrated far from their original MICS cluster. Therefore, future research should address selection biases, for example by using longitudinal data with lagged dependent variables or individual fixed-effects models. Second, we operationalized heat exposure as the mean monthly maximum temperature, aligning with much of the existing literature that uses average temperatures to capture the cumulative intensity of heat exposure (Aguilar-Gomez et al., 2024; Deschenes, 2014). However, alternative approaches exist—for example, measuring the number of days exceeding a specific temperature threshold (e.g., Park et al., 2021), and there is currently no consensus in the field on the most appropriate way to conceptualize and operationalize heat exposure when studying its impacts on human health and development (Chloe et al., 2024).

Third, while the study draws on large-scale data from six diverse countries, the results may not be generalized to other settings. Future studies should therefore further investigate the effects of heat in additional contexts. Fourth, the ECDI used in this study is a parent-reported, limited-in-scope measure of child development with relatively low precision, which introduces uncertainty into the point estimates and coefficient attenuation. Additionally, heat exposure can make children tired, unmotivated, or sleepy, potentially affecting their performance on direct assessments of early childhood development. This raises concerns about endogeneity in the measurement of developmental outcomes. Future research should account for these nuances by employing multi-method assessment approaches that combine both direct assessments and parent reports to more reliably capture the developmental impacts of excessive heat. Finally, future research should explore potential mechanisms and additional moderators that could be relevant for interventions and policy, such as families' adaptive behaviors in response to heat.

Conclusion

Collectively, this study and prior research suggest that exposure to high temperatures can undermine children's early development, particularly foundational literacy and numeracy skills, with potential downstream effects on future learning and developmental trajectories. Children in economically disadvantaged households, urban areas, and those lacking access to clean water and adequate sanitation are at a heightened risk for maladaptive outcomes due to heat. These findings underscore the urgent need for further research, policies, and interventions that promote preparedness, adaptation, and resilience in a warming world. Additionally, targeted programs for economically disadvantaged families are essential to ensure the equitable protection of human development across the course of life.

Ethical Information

Ethical approval is not applicable for this paper given that we used secondary data.

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Key points

- Climate change, along with its cascading impacts on ecosystems, societies, and communities, can affect human physical and mental health. However, little is known about how exposure to high ambient temperatures early in life might affect early childhood development
- This study used geographic and time-stamped information on children and ambient temperature in six countries to examine the effects of excessive heat on early childhood development
- We found that children exposed to average maximum temperatures above 32°C were less likely to be developmentally on track compared to those exposed to cooler temperatures, even after controlling for baseline climate and other covariates
- These findings underscore the urgent need for policies and interventions to protect human development in an increasingly warmer world.

Table 1.

Descriptive statistics

Variable	%
Child development	
ECDI (on track)	62.9
Literacy-numeracy domain (on track)	14.7
Physical domain (on track)	94.4
Social-emotional domain (on track)	72.2
Approaches to learning (on track)	83.8
Child age	
3 years	57.2
4 years	42.8
Child sex	
Male	49.7
Female	50.3
Maternal education	
Less than primary	36.2
Less than secondary	40.0
More than secondary	23.8
Area	
Urban	28.7
Rural	71.3
N	19,607

Table 2.

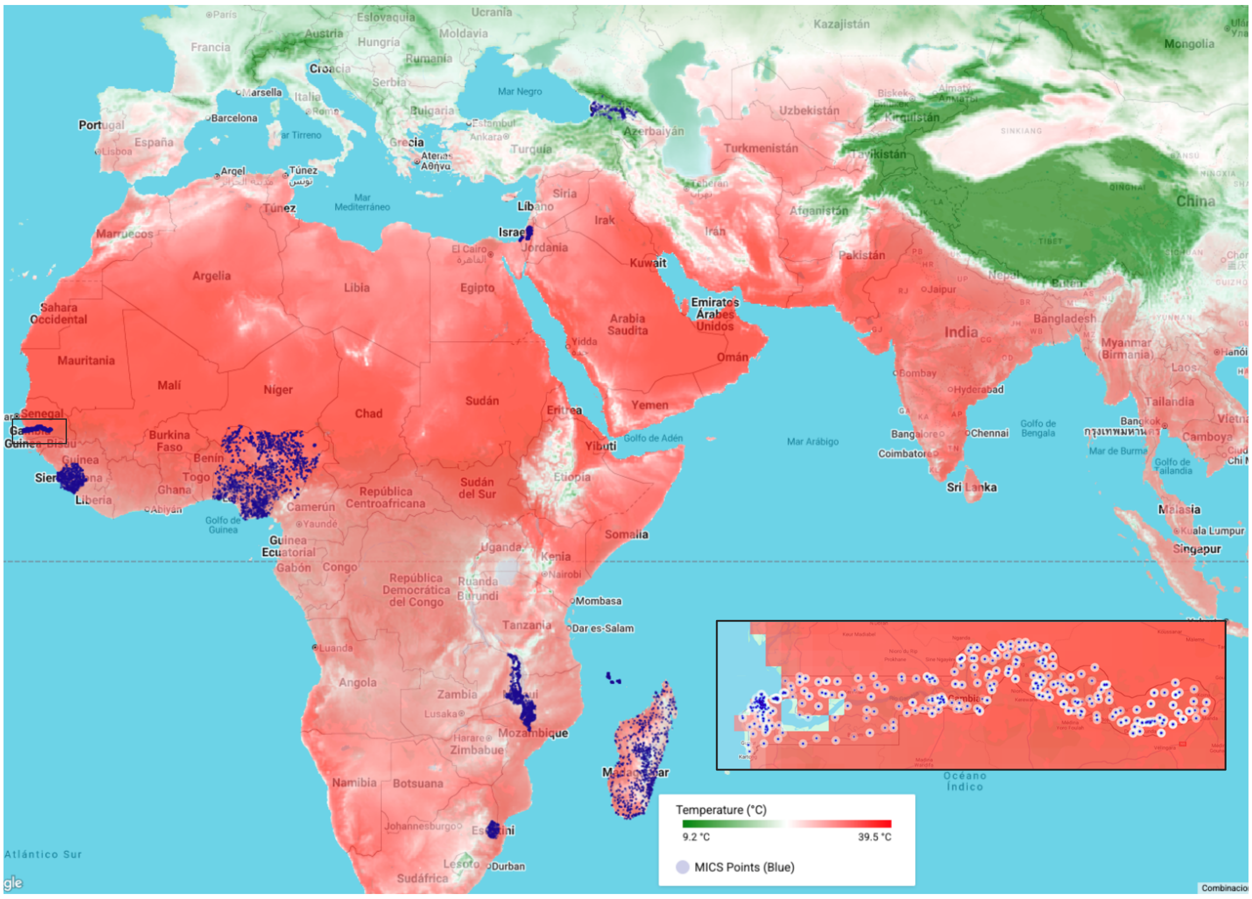
Associations between temperature bins and ECDI developmental domains

Temperature bins (°C)	ECDI domains			
	Literacy-Numeracy	Physical	Socio-emotional	Approaches to learning
<26 (reference)				
26	0.013	0.022*	-0.005	0.009
	(0.022)	(0.013)	(0.024)	(0.022)
27	-0.005	0.027	0.006	0.029
	(0.023)	(0.016)	(0.026)	(0.026)
28	0.027	0.013	-0.002	0.010
	(0.023)	(0.016)	(0.026)	(0.027)
29	-0.014	0.020	0.001	0.019
	(0.023)	(0.017)	(0.027)	(0.027)
30	-0.050*	0.027	0.002	-0.022
	(0.025)	(0.018)	(0.029)	(0.029)
31	-0.023	0.025	-0.019	-0.024
	(0.028)	(0.020)	(0.032)	(0.033)
32	-0.057*	0.009	-0.069**	-0.023
	(0.029)	(0.021)	(0.034)	(0.034)
33	-0.066**	0.031	-0.017	-0.039
	(0.029)	(0.021)	(0.035)	(0.034)
34	-0.061**	0.015	-0.020	-0.004
	(0.030)	(0.022)	(0.035)	(0.035)
≥35	-0.067**	0.020	-0.011	-0.020
	(0.032)	(0.024)	(0.040)	(0.039)
N	19,607	19,607	19,607	19,607
Clusters	3,646	3,646	3,646	3,646

Note. The table presents estimates from linear probability models, with corresponding country - cluster clustered standard errors in parentheses. All coefficients were estimated adjusting for children's age and sex, maternal education, wealth quartiles, area, dew point temperature and surface pressure, and child birthdate and interview month-year fixed effects and subnational region-country fixed-effects. *p < .05; **p < .01; ***p < .001

Figure 1.

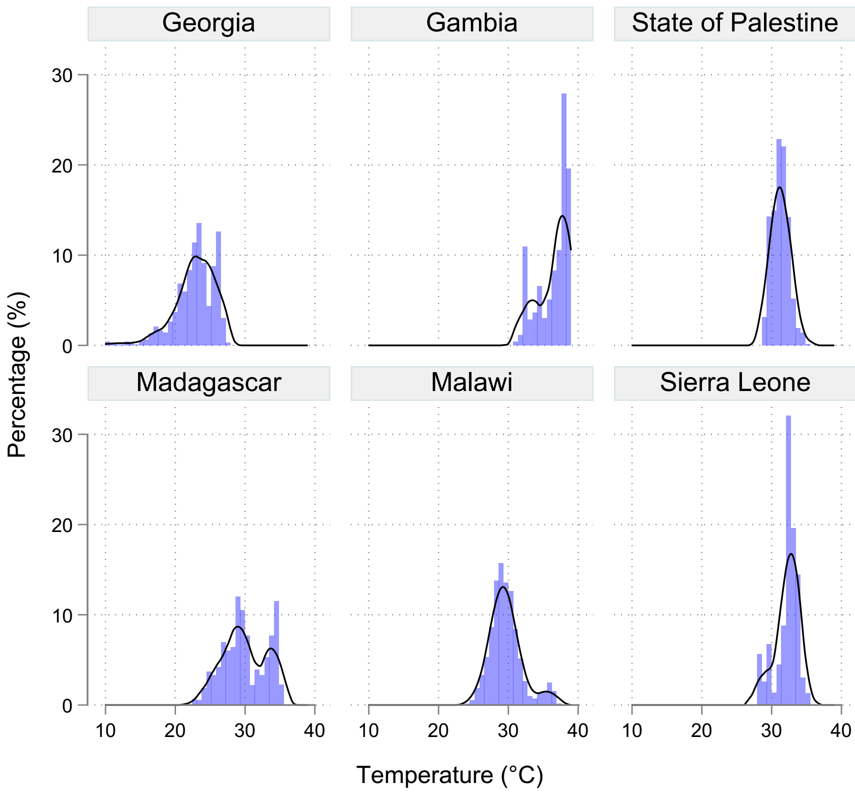
MICS clusters and maximum average temperature



Note. Darker shades of red indicate higher temperatures. Dots represent MICS clusters.

Figure 2.

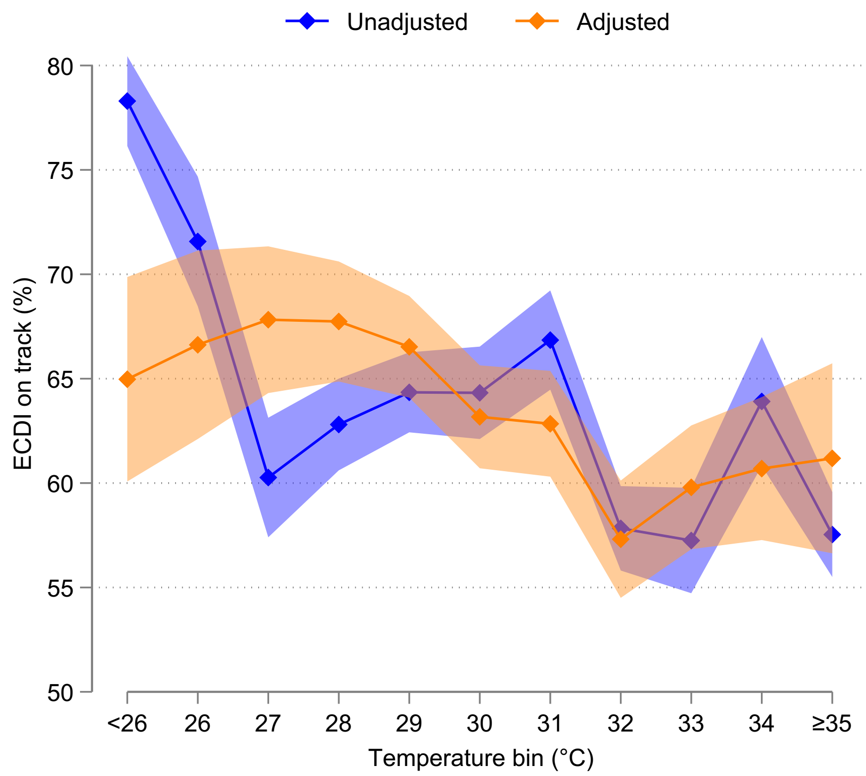
Monthly maximum temperature in sampled clusters, by country



Note. This histogram displays the distribution of the average maximum temperature from birth to interview by country in the analytic sample. The figure presents an overlaid kernel density estimate for each country.

Figure 3.

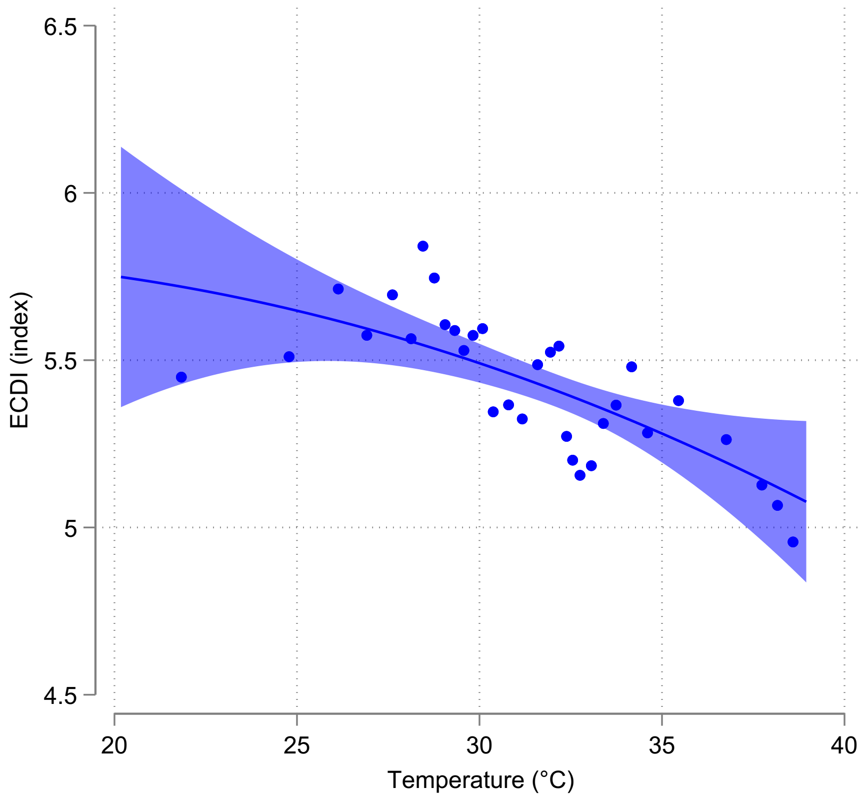
Association between temperature bins and the probability of being developmentally on track



Note: The dots represent predicted margins, and the shaded region around the estimates represent 90% confidence intervals from linear probability models for the association between temperature bins and the probability of being developmentally on track as measured by the ECDI. Adjusted model refers to a model adjusting for children's age and sex, maternal education, wealth quartiles, area, dew point temperature and surface pressure, and child birthdate and interview month-year fixed effects and subnational region-country fixed-effects.

Figure 4.

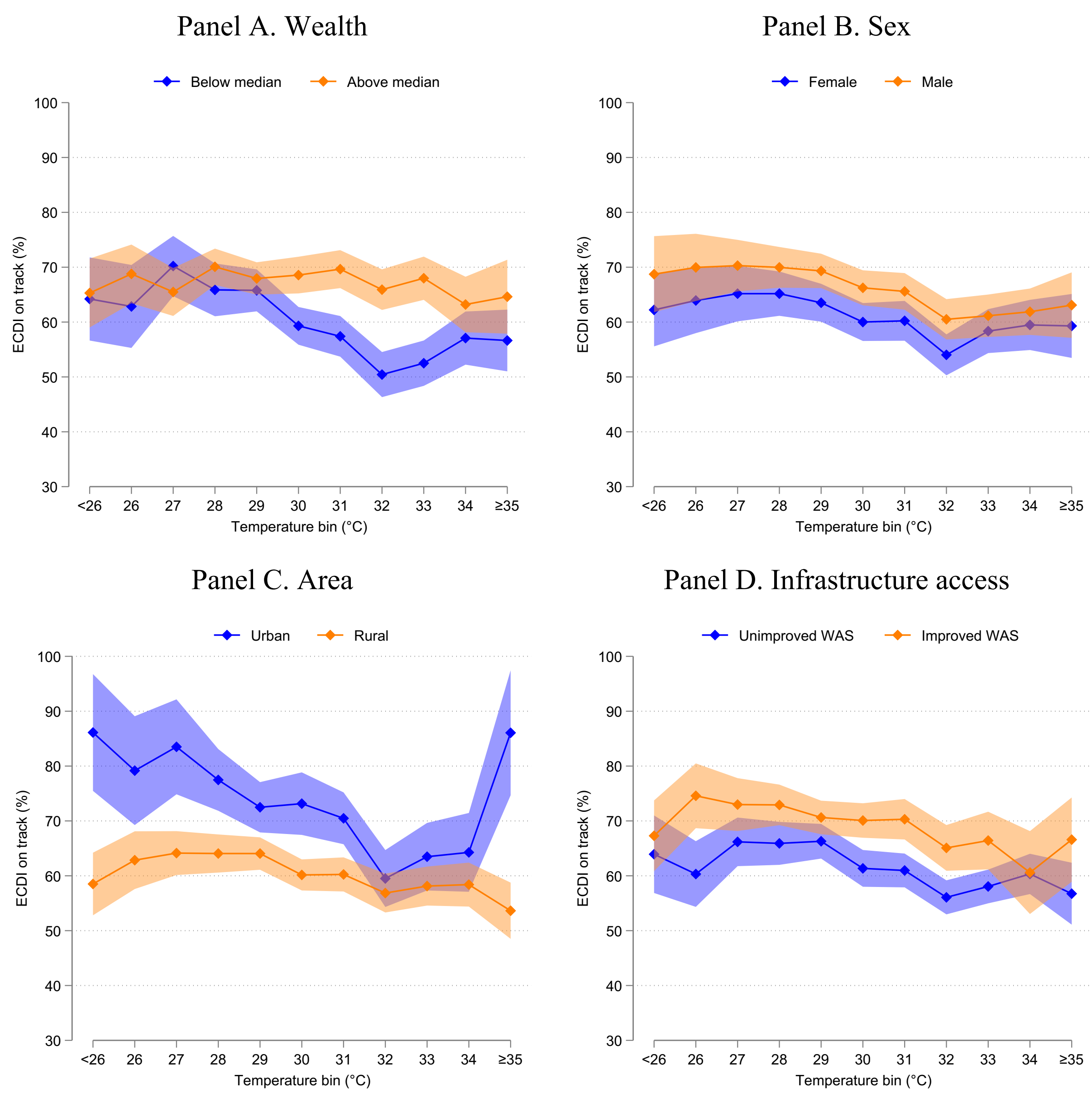
Association between ambient temperature and ECDI scores



Note. This figure presents the predicted margins and fitted regression line from a binscatter analysis of the association between the average maximum temperature from birth to interview and the overall ECDI score. Each dot represents the average ECDI score for observations within a temperature bin, plotted against the average temperature in that bin. The model controls for children's age and sex, maternal education, wealth quartiles, area, dew point temperature and surface pressure, and child birthdate and interview month-year fixed effects and subnational region-country fixed-effects.

Figure 5.

Predicted margins for the association between temperature bins and the probability of being developmentally on track by subgroups



Note. Predicted margin results by subgroups from linear probability models adjusting for children's age and sex, maternal education, wealth quartiles, area, dew point temperature and surface pressure, and child birthdate and interview month-year fixed effects and subnational region-country fixed-effects. WAS = Water and sanitation.

Running Head: HEAT AND EARLY CHILDHOOD DEVELOPMENT

Ambient Heat and Early Childhood Development: A Cross-National Analysis

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Abbreviated title: Heat and Early Childhood Development

Word Count: 4,955~~3,801~~

Abstract

Background: Increasing evidence suggests that climate change~~global warming~~, along with its cascading impacts on ecosystems, societies, and communities, has significant effects on both physical and mental health. However, less is known about how exposure to excessive heat early in life may influence the development of foundational skills that shape lifelong developmental trajectories. This study examined the effects of ambient heat on early childhood development across six countries, using geographic and time-stamped data on child development and ambient temperature. **Methods:** Our primary outcome is the Early Childhood Development Index (ECDI).~~**Methods:**~~ We used linear probability models with geographic and seasonality fixed effects to account for baseline climatic conditions, as well as other individual and contextual covariates to address potential selection bias. The sample comprised 19,607 children aged three and four from Georgia, The Gambia, Madagascar, Malawi, Sierra Leone, and The State of Palestine, all participants in ~~the sixth round of the~~ Multiple Indicators Cluster Surveys collected between 2017 and 2020.~~Survey.~~ We merged these data with temperature data from the ERA5-Land Monthly Aggregated Climate Dataset, calculating the mean monthly maximum temperature children experienced from birth to interview. **Results:** We found that children exposed to average maximum temperatures above 32~~30~~°C were less likely to be developmentally on track compared to those exposed to cooler temperatures~~ below 26°C~~, even after accounting for baseline average climatic conditions and other covariates. Domain-specific models indicate that these effects were most pronounced in literacy and numeracy skills. Subgroup analyses revealed that the negative impacts were particularly severe for children in economically disadvantaged households, urban areas, and for those lacking access to adequate water and sanitation. **Conclusions:** This study highlights the potential impact of excessive heat on early childhood development, emphasizing the need for policies and interventions that enhance

preparedness, adaptation, and resilience to support human development in an increasingly warming world.

Keywords: Heat exposure, early childhood development, climate change, temperature~~global warming~~

Abbreviations:

ECDI: Early Childhood Development Index

MICS: Multiple Indicators Cluster Survey

~~SES: Socioeconomic Status~~

Statement of Relevance

The world recorded unprecedented temperatures in 2024, and a warming planet poses significant risks to both human development and health. While much is known about the broader impacts of climate change, less attention has been given to how high temperatures affect young children's development.~~children.~~ Our study explored the effects of ambient heat on key developmental domains—literacy-numeracy, physical health, social-emotional well-being, and approaches to learning—across six countries: Georgia, The Gambia, Madagascar, Malawi, Sierra Leone, and The State of Palestine. We found that children exposed to average maximum temperatures above 32~~30~~°C were less likely to be developmentally on track compared to those exposed to cooler temperatures. Moreover, these negative effects were most pronounced for children from economically disadvantaged~~low socioeconomic~~ backgrounds, those living in rural areas, and those lacking access to clean water and adequate sanitation. These findings underscore the urgent need for policies and interventions to protect human development in an increasingly warmer world.

Ambient Heat and Early Childhood Development: A Cross-National Analysis

Climate change~~Global warming~~ is profoundly changing the ecology of human development. The year 2024 has been the warmest one on record, exceeding for the first time the 1.5° above pre-industrial levels for the annual average temperature set as a benchmark in the Paris Agreement (Romanello et al., 2024). Climate change~~Global warming~~ can increase the risk for severe storms, atypical precipitation patterns, loss of biodiversity, ocean acidification, increased pollution, and food and water scarcity, which altogether can in turn affect human societies and communities (Pörtner et al., 2022).

A warmer earth, and its cascading effects on the physical environment, societies, and communities, can undermine human health, learning, and wellbeing. Meta-analyses indicate that exposure to excessive ambient heat is associated with an increased risk for multiple physical and mental health problems in childhood and adulthood (Blom et al., 2022; Thompson et al., 2023; Weeda et al., 2024). Excessive heat can also inhibit children's and adolescents' learning and achievement in standardized tests (Park et al., 2021; Prentice et al., 2024). Moreover, hotter temperatures have been linked to an increased risk of interpersonal violence, including violence against children and gender-based violence (Evans et al., 2025; Mahendran et al., 2021)~~(Evans et al., 2023; Mahendran et al., 2021)~~.

However, there is little evidence on how exposure to excessive ambient heat early in life, which is a sensitive period of brain development, may affect the development of foundational skills (Cuartas et al., 2024; Draper et al., 2024). High ambient temperatures may affect early childhood development by causing dehydration, neuroinflammation, heightened activation of the stress response system, and disrupted sleep (Berger et al., 2023; Sorensen & Hess, 2022; Walter & Carraretto, 2016; White et al., 2007; Yan et al., 2023).~~.~~ Young children are particularly vulnerable to ambient temperatures given their heightened sensitivity to environmental input, their under-developed biological systems, —which are less capable of regulating and releasing heat via sweating, —and their dependence on adults to seek water or cooler environments (Early Childhood Scientific Council on Equity and the Environment, 2023).

Excessive ambient heat can also influence young children's development through broader ecological mechanisms. For example, extreme heat can damage crops, increase the risk of food contamination, and promote the spread of disease vectors such as mosquitoes, all of which threaten children's health and nutrition, essential foundations for healthy development (Draper et al., 2024; Kemp et al., 2022; Schlenker & Roberts, 2009). Additionally, the well-documented effects of heat on mental health may impair parenting and reduce the quality of caregiver–child interactions, both of which are critical for the development of cognitive and socio-emotional skills (Bornstein, 2015; Cuartas et al., 2024). Excessive heat may also limit children's exposure to learning opportunities by making outdoor environments less safe and contributing to more sedentary behavior (Koepp et al., 2023). Consequently, understanding the developmental effects of early exposure to heat remains critical, especially considering that over one third of children around the world are highly exposed to heatwaves and almost every child on earth is already experiencing the downstream consequences of climate change~~global warming~~ (Rees, 2021).

Understanding the developmental consequences of exposure to excessive ambient heat is challenging due to issues of selection bias (Bailey et al., 2024). Specifically, individuals with certain characteristics "self-select" to live in different settings, and some of these characteristics may predict developmental outcomes, confounding the estimated effects. Similarly, comparing children living in hot and cold regions is not informative to isolate the effects of heat on child development, as hot and cold regions may differ in factors other than temperature (e.g., ecosystemic, economic, and social) that also influence development. Multiple confounders are difficult (if not impossible) to measure and hence unobserved by researchers, exacerbating selection bias issues.

This study addresses these gaps in the literature by studying the effects of excessive ambient heat during early childhood on early childhood development skills in six countries. Following work in environmental economics (e.g., Deschenes, 2014), we mitigate concerns about selection bias by linking geocoded data on children with high-resolution longitudinal temperature data. Specifically, our approach allows for comparisons among children living within the same subnational region, thereby reducing concerns about systematic differences in climatic, economic, or social conditions across regions, while also accounting for seasonality effects.

Furthermore, we examined whether the effects of ambient heat on child development varied between wealth groups, urban versus rural settings, and household with and without access to adequate water and sanitation. These factors were selected as potential moderators because they may either mitigate or exacerbate the risks associated with excessive heat (Balza et al., 2025; Romanello et al., 2024) – for example, by providing resources to cope with heat (such as access to clean water) or by amplifying exposure and related risks (such as increased heat concentration in urban areas – known as the urban heat island effect – or contamination in households lacking adequate sanitation). Finally, given the unequal distribution of vulnerability to and gender-differentiated impact of different climate hazards (Awiti, 2022), we conducted an exploratory analysis to assess whether the effects of ambient heat differed between boys and girls.

~~This study addresses these gaps in the literature by studying the effects of excessive ambient heat on early childhood development skills in six countries, leveraging geographic and time-stamped information on children with longitudinal data on temperature. To our knowledge,~~

~~this study is the first to use a quasi-experimental approach and cross-national data to test the effects of excessive heat on early development.~~

Open Practices Statement

This study followed the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) reporting guidelines. The analyses presented in this article were not formally preregistered. Neither the data nor the materials have been archived in a permanent third-party repository. The MICS and climate data used in this study are publicly available. Geocoded information from the MICS can be obtained upon request from~~to~~ the survey developers (mics.unicef.org).

Methods

Sample & Procedures

We spatially combined data from the MICS and the ERA5-Land Monthly Aggregated Climate Dataset. Developed by UNICEF (2005), The MICS are nationally representative household surveys that employ stratified, multistage cluster sampling approaches and aim to collect internationally comparable data on children and women. Households are selected using probability proportional to size sampling within clusters, which correspond to the primary sampling~~are geographical~~ units and typically include 20-25 geographically proximate households, often within a single ~~corresponding to~~ census enumeration area~~areas~~. In this study, we used data from six countries included in the sixth round of the MICS~~ that have geolocated cluster data, that is, the geographic coordinates for each cluster of households~~: Georgia (2018), The Gambia (2018), the State of Palestine (2019–20), Madagascar (2018), Malawi (2019–20), and Sierra Leone (2017). We selected these countries because they were the only ones with available data on both geolocated household clusters, that is, geographic coordinates for each cluster, and child development, as measured by the Early Childhood Development Index (ECDI). These clusters serve as the primary units of analysis for spatial linkage with ~~the~~ climate data.

Climate data were sourced from the ERA5-Land Monthly Aggregated Climate Dataset, produced by the European Centre for Medium-Range Weather Forecasts (Hersbach et al., 2020). This dataset combines satellite observations, in-situ measurements, and numerical weather prediction models to generate consistent, continuous, and high-resolution climate records at a spatial resolution of approximately 9 kilometers (0.1 degrees). The data includes~~include~~ hourly information on surface variables, including data on temperature and precipitation, from 1950 to approximately two months before the present. We overlaid the geolocated MICS clusters with the ERA5-Land climate grids in Google Earth Engine (see Figure 1). We conducted a complete case analysis, and the~~The~~ analytic sample for this study included 19,607 children aged three and four years in 3,646 unique clusters. Table 1 presents descriptive statistics of this sample.

[FIGURE 1]

[TABLE 1]

Measures

Child Development. We used the Early Childhood Development Index (ECDI; Loizillon et al., 2017)~~((ECDILoizillon et al., 2017)~~ to assess children's early development. The ECDI is a 10-item parent-reported scale that measures basic developmental milestones between the ages of 36 to 59 months in four domains: social-emotional, literacy-numeracy, approaches to learning, and physical. The ECDI is highly policy relevant because it is a proxy indicator for the Sustainable Development Goals Indicator 4.2.1 and one of the few comparable measures of child development widely used in large-scales surveys across countries. We computed a sum index of the 10-items and then characterize children to be developmentally "on-track" if they exhibited at least 50% of each domain's relevant skills, following the developer's guidelines (Loizillon et al., 2017). In the analytic sample, almost 63% of children were developmentally on track and 37% not on track according to the ECDI.

Heat Exposure. We leveraged the geographic coordinates collected by the MICS and exact data on children's birthdates and survey interview dates to establish heat exposure. After overlaying the MICS and ERA5 data spatially, we applied a buffer of 5 kilometers around each MICS cluster point. The buffer accounts for local climate variability and random displacement of clusters, ~~—~~up to 2 km~~2km~~ in urban areas and 5–10 km in rural areas, ~~—~~carried out by the MICS to ensure respondents' privacy. Within these buffers, we followed related literature (Aguilar-Gomez et al., 2024; Deschenes, 2014) and extracted and averaged the climate variables for each buffer by month for each child, specifically calculating the mean monthly maximum temperature that children were exposed to from birth to the interview date. Due to the absence of residential history data in MICS, we assign temperature exposure based on the child's current cluster of residence, implicitly assuming residential stability from birth through the time of the survey. Figure 2 presents the distribution of maximum temperature by country for the analytic sample.

[FIGURE 2]

Covariates. Our analysis included a set of child, caregiver, household, and contextual characteristics as covariates. The MICS data provided information on children's sex and age in months, maternal education (none, primary, secondary, or more); household wealth quintiles, as measured by a composite index of dwelling characteristics and household assets; and an indicator for urban versus rural areas. We also extracted a composite measure for dew point~~dewpoint~~ temperature, which is an absolute measure of~~indicates~~ atmospheric moisture ~~content and air humidity~~, and surface pressure from the ERA5-Land as an additional atmospheric covariate. Our data also included information on children's exact birthdates, interview dates, and subnational regions (within countries) where clusters were located. Finally, we computed indicators for households' access (or lack thereof) to improved water and sanitation to assess potential heterogeneous effects of heat according to access to these basic services, following guidelines by the World Health Organization (2019)

Analytic Approach

We used the linear probability model presented in Equation 1 to estimate the relation between heat exposure and child development. In this model, Y_{igt} represented the outcome variable for child *i* in geographic area g~~cluster *d*~~ and date *t*. The model also included ~~temperature bins (i.e., ~~binary indicators for each degree Celsius, using exposure to average maximum temperatures below 26°C as the reference category (i.e., temperature bins). This threshold was informed by evidence suggesting potential adverse effects of temperatures above 26°C on mental health and behavior (Evans, 2019; Thompson et al., 2023) as well as the temperature distribution in the current sample. In this specification,~~), where~~ $Tmax_{igt}$~~x_{idt}~~ represented the mean maximum temperature bins. A binned specification is common in the related literature and allowed us to account for potential non-linear associations between heat and child development (Aguilar-Gomez et al., 2024; Deschenes, 2014)~~(Deschenes, 2014)~~.

$$Y_{igt} = \sum_{b=1}^{x} \beta_j Tmax_{igt} \sum_{b=1}^{x} \cancel{\beta_j Tmax}_{idt} + \sigma \boldsymbol{X}_i + \gamma_g + \rho_t \cancel{\rho_d} + \epsilon_{igt} \cancel{\epsilon_{idt}} \tag{1}$$

In the model, $\boldsymbol{X}_i$ was a set~~vector~~ of covariates (children's~~i.e.,~~ age and sex, maternal~~,~~ education, wealth quartiles, area, dew point temperature and surface pressure, and child birthdate)~~, etc.),~~ and γ_g and ρ_t~~ρ_d~~ denoted subnational region-country~~geographic (i.e., province or municipality)~~ fixed effects and month-year fixed effects, respectively. These fixed effects allowed us to control for seasonality effects and restrict comparisons between children ~~from different cohorts in proximal clusters ~~within the same country and same subnational region who were exposed to different average maximum temperatures due to temporal variation in temperature levels relative to their birthdates and interview dates. Causal identification thus assumed that after controlling for baseline average climatic conditions (by including geographic and seasonality fixed effects), any residual fluctuations in temperature was unexpected or exogenous.

Furthermore, we estimated additional models using the indicators for being developmentally on track for each ECDI domain as outcome variable to assess whether effects on a particular domain may drive the observed associations with the overall ECDI. We also conducted two sensitivity analyses to test the robustness of the results. First, although the selection of 26°C as the reference category in our binned specification was informed by prior evidence, we also conducted a data-driven~~First, we estimated a~~ binscatter least squares estimation as a sensitivity check. In this approach,~~using~~ the continuous ~~variables for~~ temperature variable is divided into intervals (or bins), and each point in the plot represents the average ECDI ~~total~~ score within a temperature bin, plotted against the average temperature in that bin, allowing us to visualize the underlying functional relationship while smoothing out noise.~~instead of categorical variables.~~ Second, we estimated probit and logistic regression models instead of linear probability models, which account for the bounded nature of binary outcomes and allow for nonlinear relationships between the predictors and the probability of the outcome, providing a useful check on whether our findings are sensitive to the functional form of the model and distributional assumptions.

Finally, we assessed potential moderating effects or heterogeneity in the observed associations by estimating independent effects for different subgroups, including: (1) ~~each~~ wealth below and above the median~~quartile~~, (2) urban versus rural, and (3) those with and without access to both improved water and improved sanitation. These analyses are helpful to understand the potential risk factors that may compound the effects of heat on early child development.

Results

Estimates of the Effects of Heat on Early Child Development

Figure 3 summarizes results from our primary linear probability regression analysis estimating the association between temperature bins and being developmentally on track according to the ECDI. The Figure presents predicted margins (i.e., model-based predicted probabilities of the outcome at specific values of the independent variable) for the unadjusted model which does not include any covariates, and for the model including all covariates and geographic~~spatial~~ and temporal fixed effects. The unadjusted estimates show a clear gradient, with children experiencing hotter average temperatures having a lower likelihood of being developmentally on track. For example, children who were exposed to an average maximum temperature of more than 30°C were between 14 (SE=0.019) and 20.8 (SE=0.018) percentage points less likely to be developmentally on track compared to those who were exposed to average maximum temperatures experienced lower than 26°C. The adjusted model, including all covariates and~~,~~ our preferred model, showed that some, ~~—~~but not all, ~~—~~of these associations may be due to confounding. Specifically, it showed that children who were exposed to an average maximum temperature of 32°C were between 1.8 (SE=0.033) and 7.7 (SE=0.039) percentage points less likely to be developmentally on track compared to those who were exposed to average maximum temperatures lower than 26°C, with some bins not reaching statistical significance but being consistent in directionality. In general, both models showed the same drop in the probability of children being on track after exposure to average maximum temperatures higher than 30°C–31°C.

[FIGURE 3]

Table 2 presents results for the ECDI domain-specific analysis. Children who were exposed to monthly average maximum temperatures above 30°C had lower probabilities of being developmentally on track in the literacy-numeracy domain, with a statistically significant association ranging between 5 (SE=0.025) and 6.7 (SE=0.032) percentage points, relative to those who were exposed to average maximum temperatures lower than 26°C. We also observed a statistically significant association between temperatures of 32°C and a 6.9 (SE=0.034) percentage points lower likelihood of being developmentally on track in the socio-emotional domain, relative to temperatures below 26°C. Similarly, temperatures of 26°C are associated with a 2.2 (SE=0.013) percentage point higher likelihood of being on track in the physical domain relative to temperatures below 26°C.

[TABLE 2]

Figure 4 presents estimates from an alternative data-driven binscatter least squares estimation using continuous ECDI total scores and including all control variables~~variable~~ and geographic~~spatial~~ and temporal fixed-effects. The results were consistent with findings from our main specification, showing a negative association between ambient temperature and ECDI scores after accounting for baseline average climatic conditions and other individual and contextual covariates. Moreover, the predicted margins~~marginal effects~~ estimated using the probit and logit models were consistent with those from the linear probability model (see supplemental files, Figure S1~~Table 3~~).

[FIGURE 4]

Finally, while the main goal of this study was to assess the potential effects of excessive heat exposure from birth to the MICS interview date, extensive evidence also indicates that in-utero exposure to excessive heat can negatively impact human development outcomes (Brink et al., 2024). Consequently, we conducted a sensitivity analysis to examine the association between prenatal exposure to excessive heat and being developmentally on track (ECDI), assuming an average pregnancy duration of nine months. Our results, presented in Table S2 (supplemental files), show somewhat inconsistent association between temperature bins and the ECDI. We observed statistically significant associations between temperatures of 26°C and 27°C in the first trimester of pregnancy and a 4.1 (SE=0.020) and 3.3 (SE=0.018) percentage points higher likelihood of being developmentally on track, as well as between temperatures of 33°C and a 3.5 percentage points (SE=0.020) lower probability of ECDI on-track, relative to temperatures below 26°C. Moreover, temperatures of 34°C in the third trimester were associated to a 4.2 lower likelihood (SE=0.020) of being developmentally on track relative to temperatures below 26°C. These results align with recent evidence on how heat can exacerbate risks for neurodevelopment early and late in pregnancy (Lin et al., 2025).

~~[TABLE 3]~~

Heterogeneity in the Effects of Heat Exposure on Early Child Development

Subgroup analyses revealed pronounced heterogeneity in the association between heat exposure and early childhood development (Figure 5). Children from economically~~socioeconomically~~ disadvantaged households appear to bear a disproportionately higher burden. For example, children below~~in~~ the median~~lowest wealth quartile~~ experienced a reduced likelihood of being developmentally on track as temperatures increased, whereas this trend is not evident for those at~~in~~ the top of the~~highest~~ wealth distribution~~quartile~~. In addition, area-based differences emerge, with children exposed to high ambient temperatures and living in urban areas experiencing between 21.9 (SE=0.091) and 26.6 (SE=0.087) percentage points reductions in the likelihood of being developmentally on track, whereas those in rural areas did not experience such effects. Finally, children in households lacking improved water sources experienced stronger reductions in their likelihood of being developmentally on track when exposed to high heat (up to 13.9 percentage points, SE=0.082).

[FIGURE 5]

Discussion

Climate projections suggest that current actions (and inactions) by governments and societies could lead to a temperature increase of 2.1°C to 3.9°C above pre-industrial levels (Climate Action Tracker, 2024; Kemp et al., 2022). A warmer world may trigger cascading effects, including rising sea levels, more frequent extreme weather events, the spread of vector-borne diseases, loss of ecosystem services, forced displacement, macroeconomic instability, conflict, resource shortages, and negative impacts on both physical and mental health (Kemp et al., 2022; Romanello et al., 2024). Despite the widespread recognition of these risks, including advocacy and discussion pieces highlighting the dangers of excessive heat for children (Early Childhood Scientific Council on Equity and the Environment, 2023; Rees, 2021), research linking ambient heat to early childhood development remains limited. This study leveraged novel spatial and temporal data to examine how excessive heat may impact the development of foundational skills in young children across six countries that vary in terms of socioeconomic characteristics, culture, and climatic conditions.

We found that children exposed to monthly average maximum temperatures above 30°C were less likely to be developmentally on track compared to those exposed to cooler~~average~~ temperatures. This association was consistent~~ below 26°C,~~ even after controlling for baseline average climatic conditions, by comparing children in the same subnational region and adjusting for seasonality effects, as well as other individual and contextual factors. These findings align with literature across multiple disciplines highlighting the environmental, health, and behavioral risks that high temperatures pose to early child development. For example, warm temperatures tend to accelerate the proliferation of disease vectors and bacteria that cause gastrointestinal and respiratory illnesses (Kemp et al., 2022). Similarly, crop yields are adversely affected at temperatures above 34°C, and warmer conditions also heighten the risk of food contamination, which in turn threatens children's health and nutrition and therefore development (Schlenker & Roberts, 2009). For example, one study estimated that a 2°C temperature increase could lead to a 7.4 percentage point rise in stunting, while temperatures exceeding 30°C are associated with a 2.2 percentage point increase in wasting rates (Blom et al., 2022). Finally, temperatures above 26~~27~~°C can also increase adults' mental health conditions, aggression, and interpersonal violence, with potential downstream effects on children's safety and development (Evans, 2019; Thompson et al., 2023).

Domain-specific analyses suggest that the impact of heat on early child development may be particularly driven by its effects on cognitive literacy-numeracy skills, which aligns with prior research showing the adverse effects of heat on cognition. For example, temperatures above 32°C have been linked to a nearly 10% reduction in adult cognitive function and accelerated cognitive decline in the adult population (Choi et al., 2023; Yin et al., 2024). Similarly, temperatures above 26.7°C can impair cognitive performance in children and adolescents (Park, 2022; Park et al., 2021).~~(Park, 2022; Park et al., 2021).~~ Excessive heat can impact cognitive development directly (Piil et al., 2020) and indirectly through several mechanisms, including dehydration, increased activation of the stress response system, neuroinflammation, damage to nerve cells due to inadequate heat dissipation, and disrupted sleep (Berger et al., 2023; Sorensen & Hess, 2022; Walter & Carraretto, 2016; White et al., 2007; Yan et al., 2023). Similarly, it can reduce children's physical activity, increase sedentary behavior, and reduce opportunities for interaction with others outside the home (Koepp et al., 2023).

Conceptually, the same~~these~~ mechanisms linking excessive heat with cognitive outcomes could also affect children's physical and social-emotional development. However, in our sample~~; however~~, the evidence for such associations ~~in our current sample~~ was less consistent. We found a statistically significant association between temperatures of 32 °C and a lower likelihood of being developmentally on track in the socio-emotional domain, but not at higher temperatures. This inconsistent pattern may reflect measurement limitations in socio-emotional development relative to the literacy-numeracy domain, as noted in prior research (McCoy et al., 2016). Similarly, we observed a positive association between temperatures of 26 °C and physical development, relative to cooler days, but again no consistent effects at higher temperatures. These mixed findings suggest caution in interpreting the effects of heat on physical and socio-emotional development in this sample. It is also possible that the effects of early-life heat exposure emerge more clearly in cognitive outcomes during early childhood, with impacts on other domains, such as socio-emotional functioning becoming evident only later in life. Future studies using more precise measures and longitudinal designs are needed to clarify these patterns.

We also found that the effect of high temperatures on early child development is heterogeneous, with particularly severe effects on children from economically disadvantaged~~living in low-socioeconomic status (SES)~~ households, urban areas, and households with limited access to essential services. Families from economically disadvantaged~~low-SES~~ backgrounds and in urban areas are more likely to live in housing and areas that trap heat and are less likely to have access to air conditioning, public cooling spaces, and clean drinking water, which increases the risk for heat stress and children's exposure to heat-related hazards (El Khayat et al., 2022; Gronlund, 2014). Furthermore, combined with inadequate access to water, which was found to be a significant moderator~~ and sanitation~~, heat exacerbates the risks of water scarcity, contamination, and disease transmission. Exposure to pollutants and contamination during early childhood can disrupt synapse development in key brain areas, thereby impairing children's cognitive and social-emotional developments (Walker et al., 2011). Conversely, access to adequate water ~~and sanitation~~ can act as a protective buffer against the detrimental effects of heat on children by offering a readily available means of cooling (Balza et al., 2025).

Findings from the heterogeneity analyses highlight the urgent need to prioritize support for economically disadvantaged~~. These findings therefore underscore the importance of supporting low-SES~~ communities in efforts~~and ensuring reliable infrastructure for water and sanitation as a key policy priority~~ to mitigate heat-related risks to early childhood development. A critical area of investment, as suggested by the current results, is the provision of reliable water and sanitation infrastructure, which can offer opportunities for cooling and reduce exposure to heat-related contaminants. Additional support may include cash transfer programs, which can enhance families' ability to access resources needed to cope with extreme heat, and the distribution of cooling tools, such as fans. Furthermore, the finding that heat effects are more pronounced in urban compared to rural areas, consistent with the urban heat island effect, underscores the importance of ecological and infrastructure-based interventions, including increasing vegetation cover, implementing cool surface technologies, and enhancing urban infrastructure to support temperature regulation~~child development~~.

Limitations

This study makes significant contributions to the literature on the developmental consequences of excessive ambient heat, but it also has limitations. First, although we accounted for baseline average climatic conditions and other potential confounders, there may still be unobserved factors that could have biased the results. Additionally, while we can accurately assign temperature levels to children who remained in the same cluster throughout their lives, this is not possible for those who migrated far from their original MICS cluster. Therefore, future research should address selection biases, for example by using longitudinal data with lagged dependent variables or individual fixed-effects models. Second, we operationalized heat exposure as the mean monthly maximum temperature, aligning with much of the existing literature that uses average temperatures to capture the cumulative intensity of heat exposure

(Aguilar-Gomez et al., 2024; Deschenes, 2014). However, alternative approaches exist—for example, measuring the number of days exceeding a specific temperature threshold (e.g., Park et al., 2021), and there is currently no consensus in the field on the most appropriate way to conceptualize and operationalize heat exposure when studying its impacts on human health and development (Chloe et al., 2024).

Third~~Second~~, while the study draws on large-scale data from six diverse countries, the results may not be generalized to other settings. Future studies should therefore further investigate the effects of heat in additional contexts. Fourth~~Third~~, the ECDI used in this study is a parent-reported, limited-in-scope measure of child development with relatively low precision, which introduces uncertainty into the point estimates and coefficient attenuation. Additionally, heat exposure can make children tired, unmotivated, or sleepy, potentially affecting their performance on direct assessments of early childhood development. This raises concerns about endogeneity in the measurement of developmental outcomes. Future research should account for these nuances by employing multi-method assessment approaches that combine both~~incorporate~~ direct assessments and parent reports to more reliably capture the developmental impacts of excessive heat.~~reliable measures of child development.~~ Finally, future research should explore potential mechanisms and additional moderators that could be relevant for interventions and policy, such as families' adaptive behaviors in response to heat.

Conclusion

Collectively, this study and prior research suggest that exposure to high temperatures can undermine children's early development, particularly foundational literacy and numeracy skills, with potential downstream effects on future learning and developmental trajectories. Children in economically~~socioeconomically~~ disadvantaged households, urban areas, and those lacking access to clean water and adequate sanitation are at a heightened risk for ~~the~~ maladaptive outcomes due to heat. These findings underscore the urgent need for further research, policies, and interventions that promote preparedness, adaptation, and resilience in a warming world. Additionally, targeted programs for economically disadvantaged families are essential to ensure the equitable protection of human development across the course of life.

Ethical Information

Ethical approval is not applicable for this paper given that we used secondary data.

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Key points

- Climate change~~Global warming~~, along with its cascading impacts on ecosystems, societies, and communities, can affect human physical and mental health. However, little is known about how exposure to high ambient temperatures early in life might affect early childhood development
- This study used geographic and time-stamped information on children and ambient temperature in six countries to examine the effects of excessive heat on early childhood development
- We found that children exposed to average maximum temperatures above 32~~30~~°C were less likely to be developmentally on track compared to those exposed to cooler temperatures~~ below 26°C~~, even after controlling for baseline climate and other covariates
- These findings underscore the urgent need for policies and interventions to protect human development in an increasingly warmer world.

Table 1.

Descriptive statistics

Variable	%
Child development	
ECDI (on track)	62.9~~90~~
Literacy-numeracy domain (on track)	14.7~~70~~
Physical domain (on track)	94.4~~40~~
Social-emotional domain (on track)	72.2~~20~~
Approaches to learning (on track)	83.8~~80~~
Child age	
3 years	57.2~~20~~
4 years	42.8~~80~~
Child sex	
Male	49.7~~70~~
Female	50.3~~30~~
Maternal education	
Less than primary	36.2~~10~~
Less than secondary	40.0~~00~~
More than secondary	23.8~~80~~
Area	
Urban	28.7~~70~~
Rural	71.3~~30~~
N	19,607

Table 2.

Associations between temperature bins and ECDI developmental domains

	ECDI domains			
Temperature bins (°C)	Literacy-Numeracy	Physical	Socio-emotional	Approaches to learning
<26 (reference)				
26	0.013	0.022*	-0.005	0.009
	(0.022)	(0.013)	(0.024)	(0.022)
27	-0.005	0.027	0.006	0.029
	(0.023)	(0.016)	(0.026)	(0.026)
28	0.027	0.013	-0.002	0.010
	(0.023)	(0.016)	(0.026)	(0.027)
29	-0.014	0.020	0.001	0.019
	(0.023)	(0.017)	(0.027)	(0.027)
30	-0.050*	0.027	0.002	-0.022
	(0.025)	(0.018)	(0.029)	(0.029)
31	-0.023	0.025	-0.019	-0.024
	(0.028)	(0.020)	(0.032)	(0.033)
32	-0.057*	0.009	-0.069**	-0.023
	(0.029)	(0.021)	(0.034)	(0.034)
33	-0.066**	0.031	-0.017	-0.039
	(0.029)	(0.021)	(0.035)	(0.034)
34	-0.061**	0.015	-0.020	-0.004
	(0.030)	(0.022)	(0.035)	(0.035)
≥35~~+~~	-0.067**	0.020	-0.011	-0.020
	(0.032)	(0.024)	(0.040)	(0.039)
N	19,607	19,607	19,607	19,607
Clusters	3,646	3,646	3,646	3,646

Note. The table presents estimates~~Results~~ from linear probability models, with corresponding country - cluster clustered standard errors in parentheses. All coefficients were estimated adjusting for children's age and sex, maternal education, wealth quartiles, area, dew point~~dewpoint~~ temperature and surface pressure, and child birthdate and interview month-year fixed effects and subnational region-country fixed-effects. *p < .05; **p < .01; ***p < .001

~~**Table 3.**~~

~~*Marginal effects for the association between temperature bins and the probability of being developmentally on track from Probit and Logit models*~~

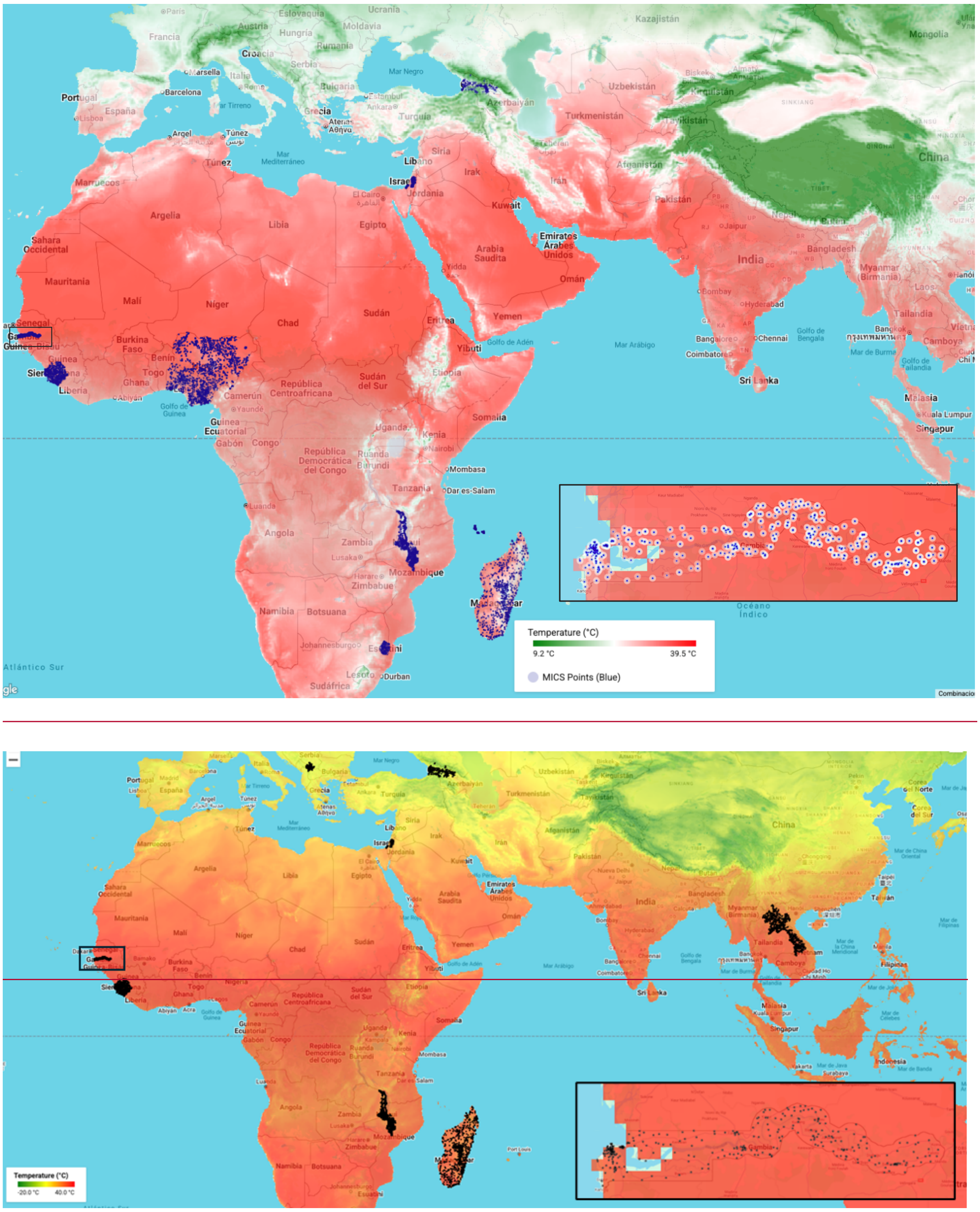
Temperature bins (°C)	Unadjusted		Adjusted	
	Probit	Logit	Probit	Logit
<26 (reference)				
26	-0.067***	-0.067***	0.021	0.018
	(0.019)	(0.019)	(0.024)	(0.025)
27	-0.180***	-0.180***	-0.031	-0.031
	(0.019)	(0.019)	(0.025)	(0.025)
28	-0.155***	-0.155***	-0.021	-0.022
	(0.016)	(0.016)	(0.024)	(0.024)
29	-0.140***	-0.140***	-0.027	-0.028
	(0.015)	(0.015)	(0.023)	(0.023)
30	-0.140***	-0.140***	-0.040	-0.042*
	(0.016)	(0.016)	(0.025)	(0.025)
31	-0.114***	-0.114***	-0.033	-0.033
	(0.016)	(0.016)	(0.027)	(0.027)
32	-0.205***	-0.205***	-0.074***	-0.074***
	(0.014)	(0.014)	(0.027)	(0.027)
33	-0.210***	-0.210***	-0.055**	-0.056**
	(0.016)	(0.016)	(0.027)	(0.027)
34	-0.144***	-0.144***	-0.055**	-0.055**
	(0.017)	(0.017)	(0.028)	(0.028)
35+	-0.208***	-0.208***	-0.094***	-0.096***
	(0.014)	(0.014)	(0.031)	(0.031)
N	19,607	19,607	19,607	19,607
Clusters	3,646	3,646	3,646	3,646

~~*Note.*~~

~~Results from probit and logit models. Covariates include children's age and sex, maternal education, wealth quartiles, area, dewpoint temperature and surface pressure, and child birthdate and interview month-year fixed effects and region fixed-effects. *p < .05; **p < .01; ***p < .001~~

Figure 1.

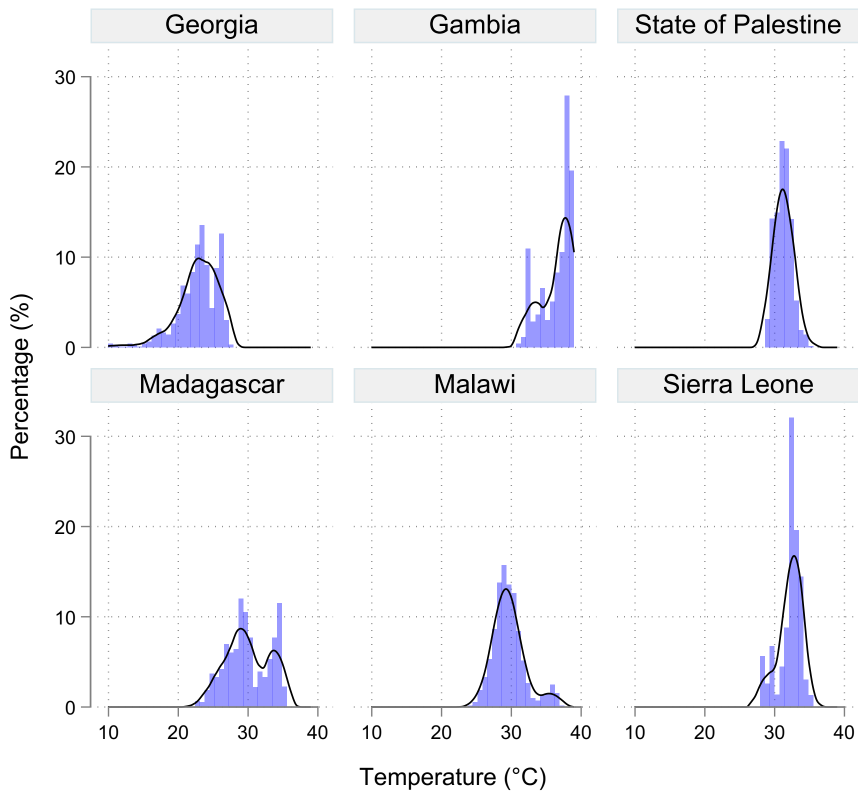
MICS clusters and maximum average temperature

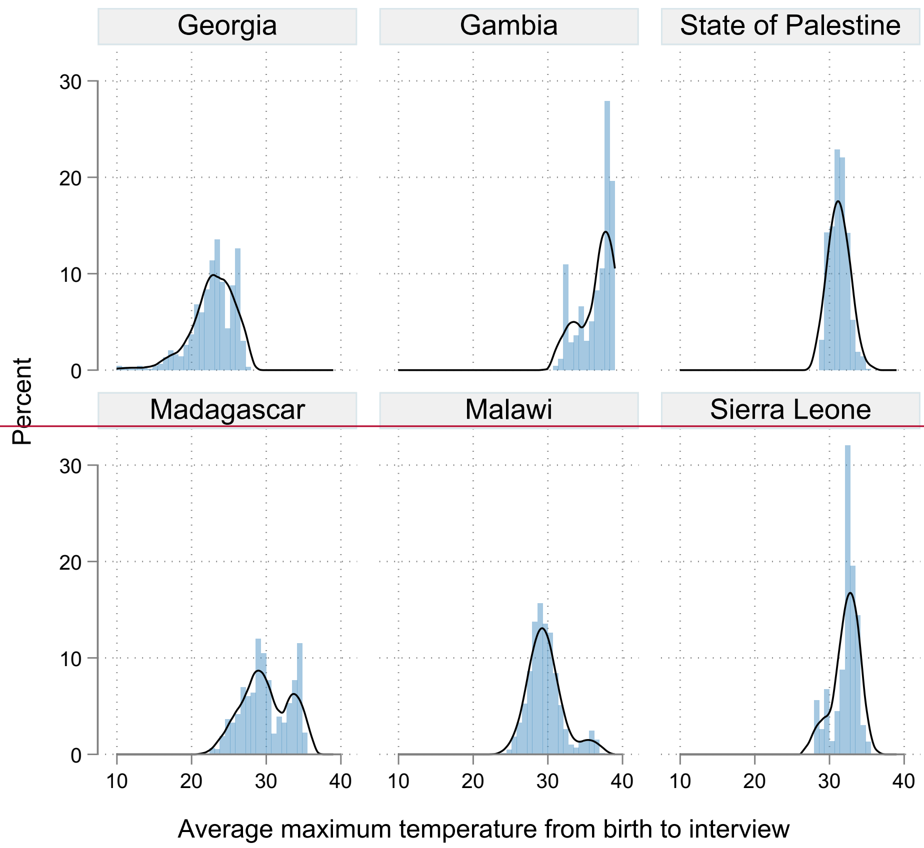


Note. Darker shades of red indicate higher temperatures. Dots represent MICS clusters.

Figure 2.

Monthly maximum temperature in sampled clusters, by country

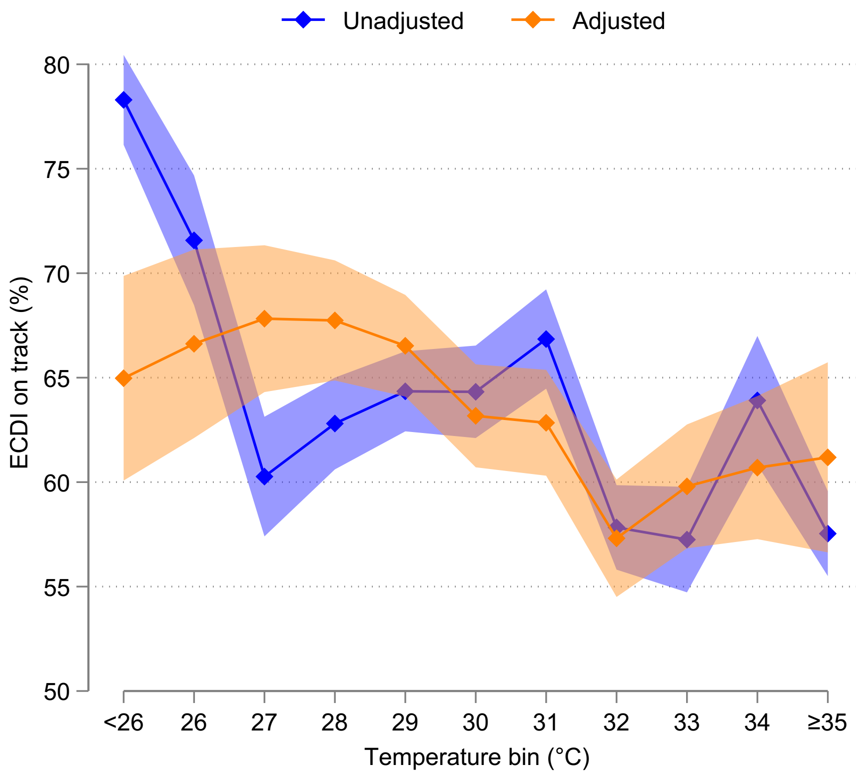




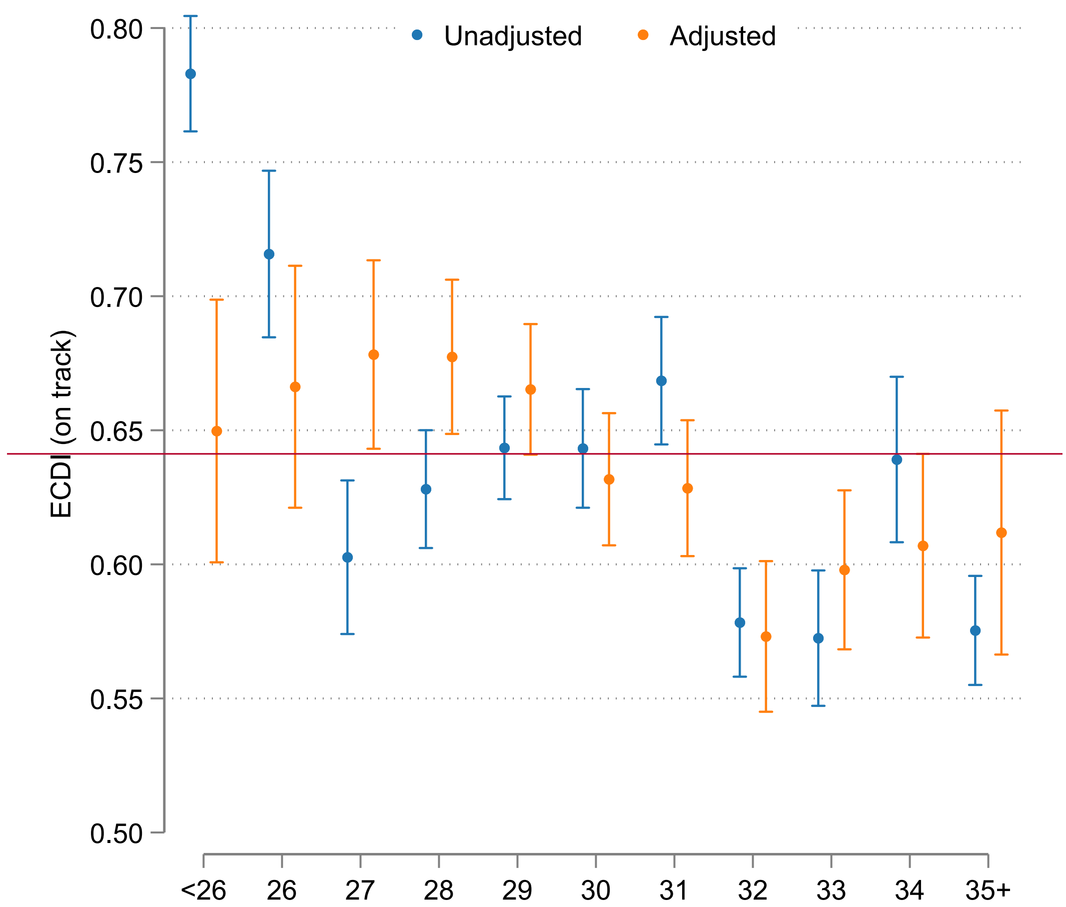
Note. This histogram displays the distribution of the average maximum temperature from birth to interview by country in the analytic sample. The figure presents an overlaid kernel density estimate for each country.

Figure 3.

Association between temperature bins and the probability of being developmentally on track



Unadjusted
Adjusted
80
75
70
65
60
55
50
ECDI on track (%)
<26
26
27
28
29
30
31
32
33
34
≥35
Temperature bin (°C)

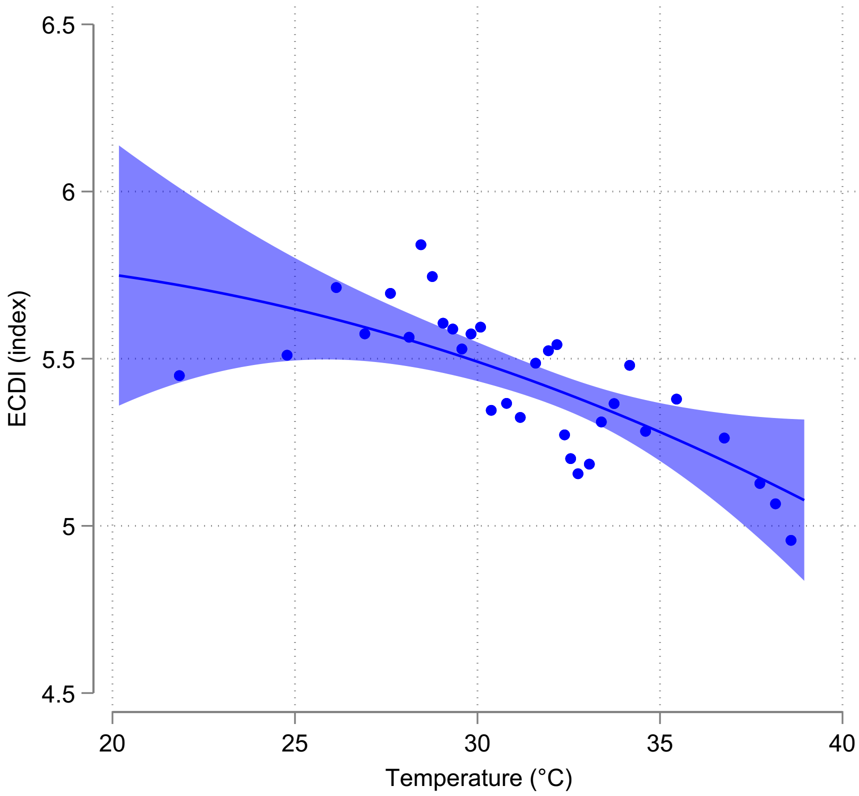


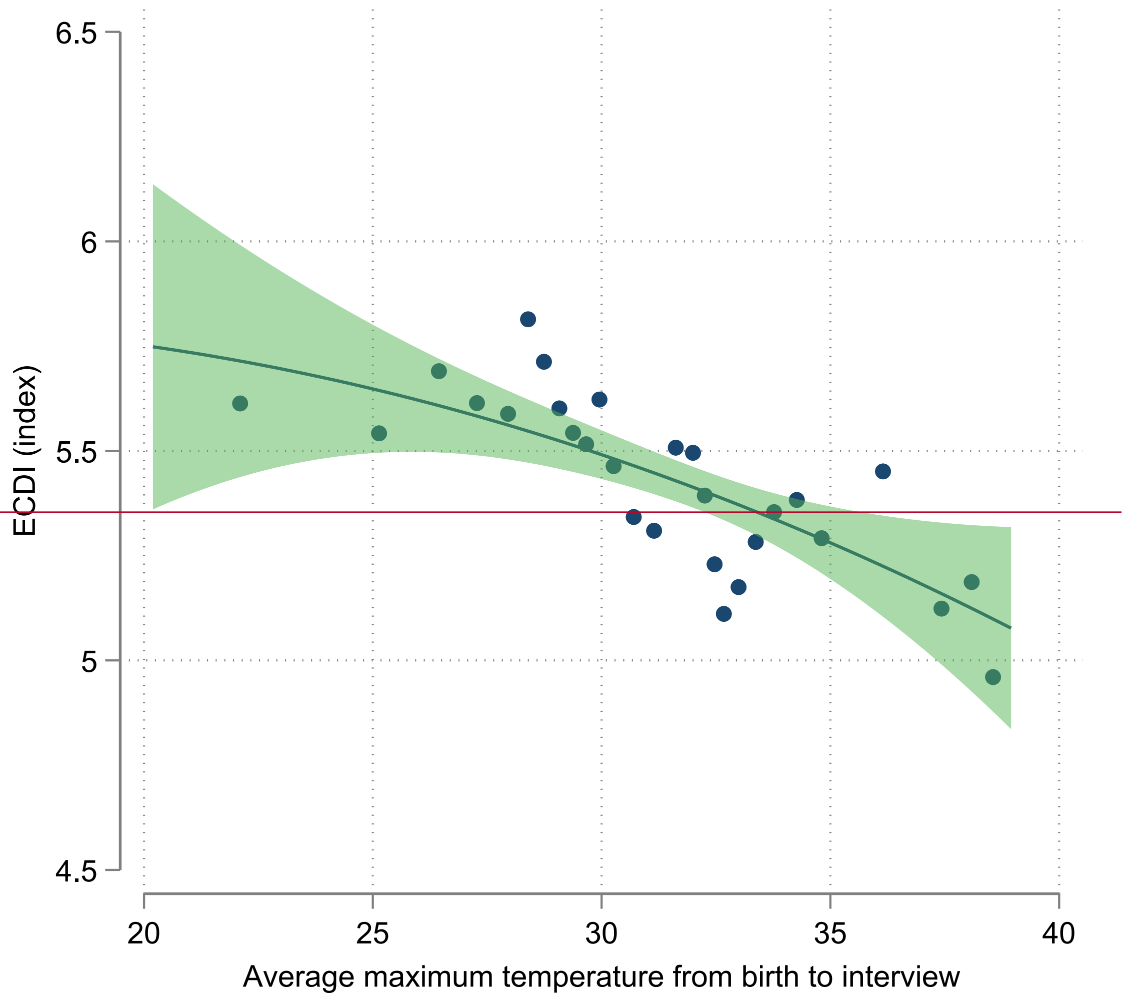
Note: The dots represent predicted~~Predicted~~ margins, and the shaded region around the estimates represent ~~(with~~ 90% confidence intervals~~)~~ from linear probability models for the association between temperature bins and the probability of being developmentally on track as measured by the ECDI. Adjusted~~Unadjusted~~ model refers to a model adjusting for children's age and sex, maternal education, wealth quartiles, area, dew point~~dewpoint~~ temperature and surface pressure, and child birthdate and interview month-year fixed effects and subnational region-country fixed-effects.

~~When the confidence interval overlaps, the coefficient on the exposure indicator is not statistically significant from the reference group.~~

Figure 4.

Association between ambient temperature and ECDI scores


6.5
6
5.5
5
4.5
ECDI (index)
20
25
30
35
40
Temperature (°C)

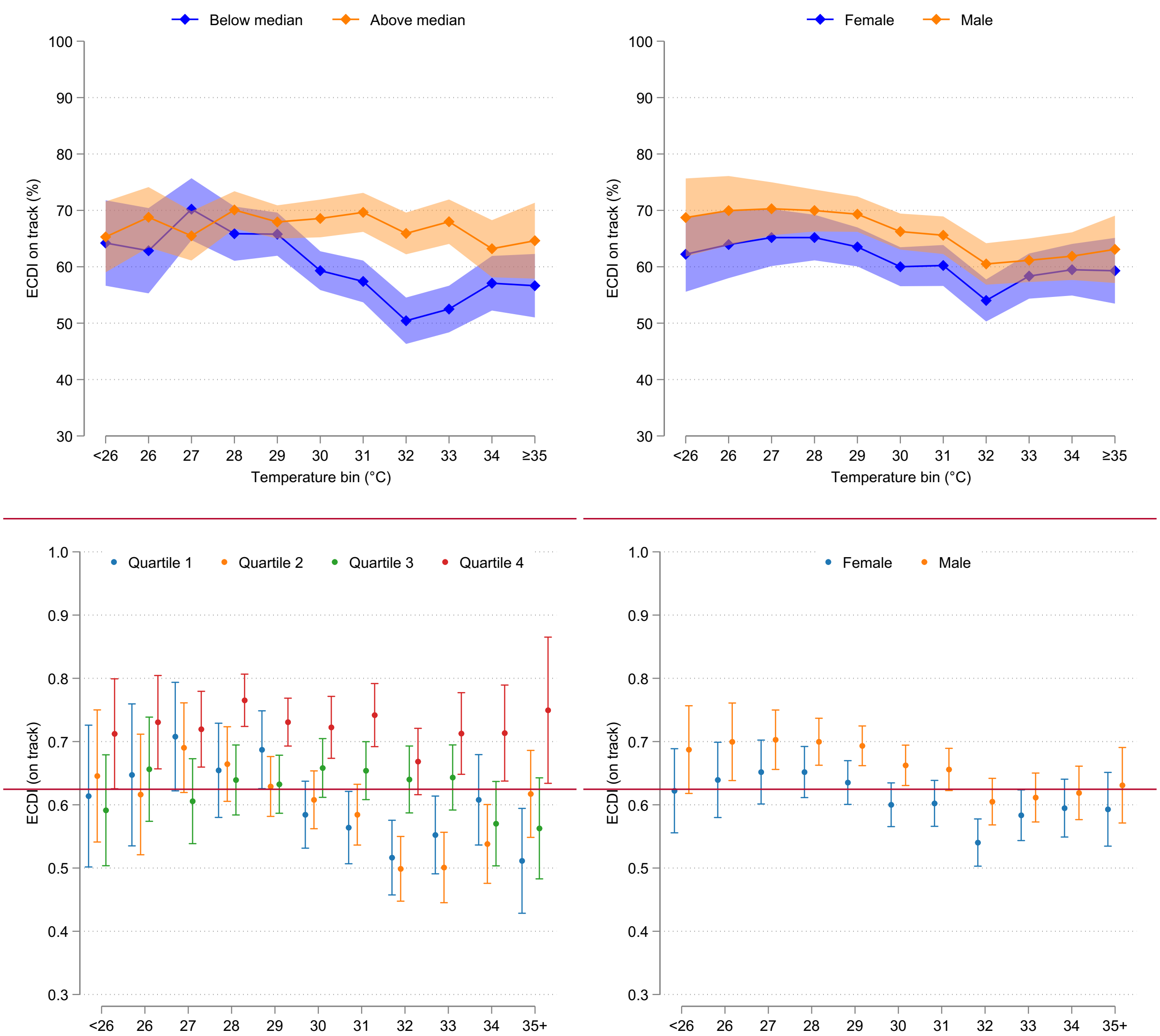


Note. This figure presents the predicted margins and fitted regression line from a binscatter analysis of the association between the average maximum temperature from birth to interview and the overall ECDI score. Each dot represents the average ECDI score for observations within a temperature bin, plotted against the average temperature in that bin. The model controls for children's age and sex, maternal education, wealth quartiles, area, dew point~~dewpoint~~ temperature and surface pressure, and child birthdate and interview month-year fixed effects and subnational region-country fixed-effects.

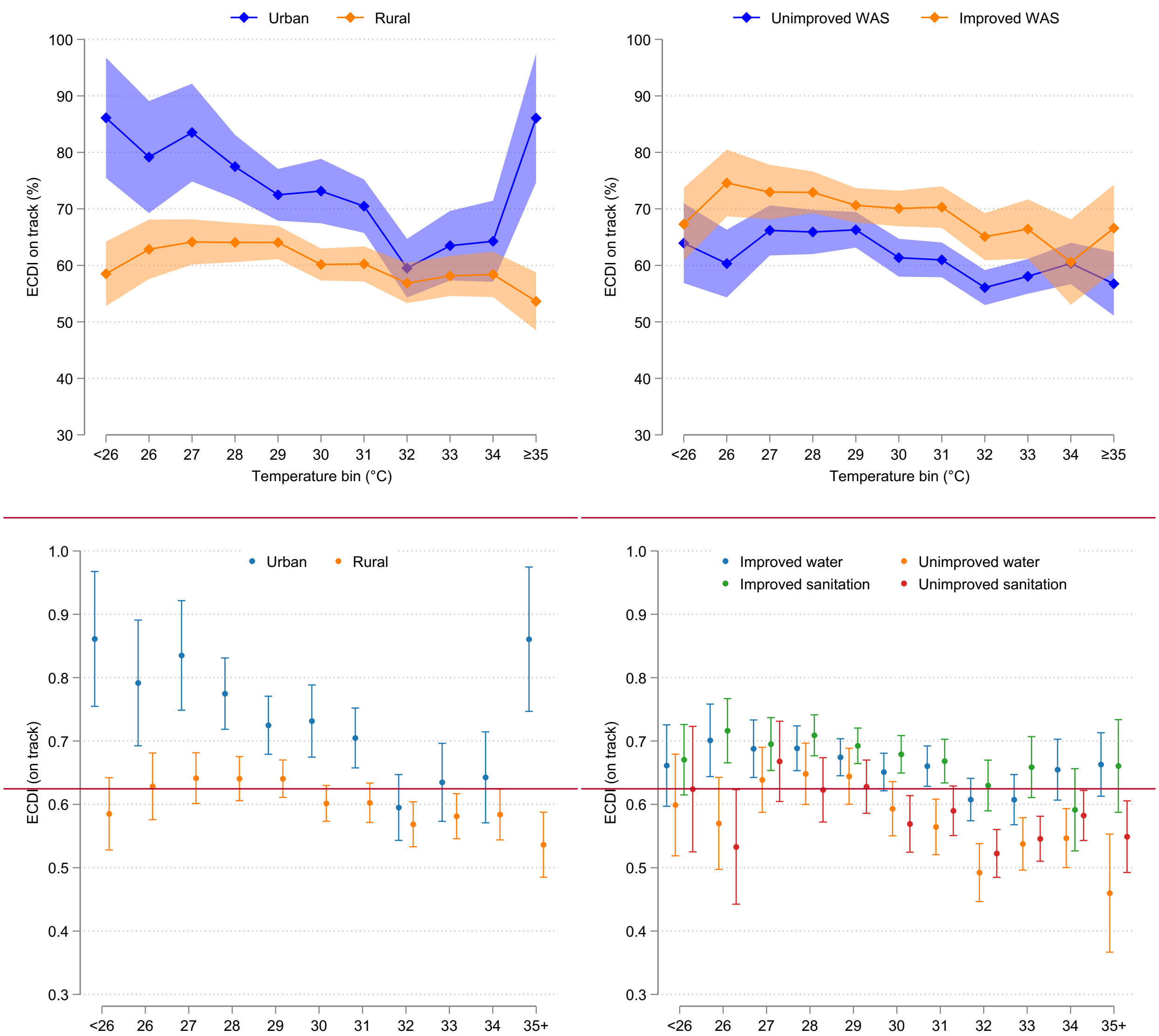
Figure 5.

Predicted margins for the association between temperature bins and the probability of being developmentally on track by subgroups

Panel A. Wealth ~~quartiles~~ Panel B. Sex



Panel C. Area Panel D. Infrastructure access



Note. Predicted margin results by subgroups from linear probability models adjusting for children's age and sex, maternal education, wealth quartiles, area, dew point~~dewpoint~~ temperature and surface pressure, and child birthdate and interview month-year fixed effects and subnational region-country fixed-effects. WAS = Water and sanitation.

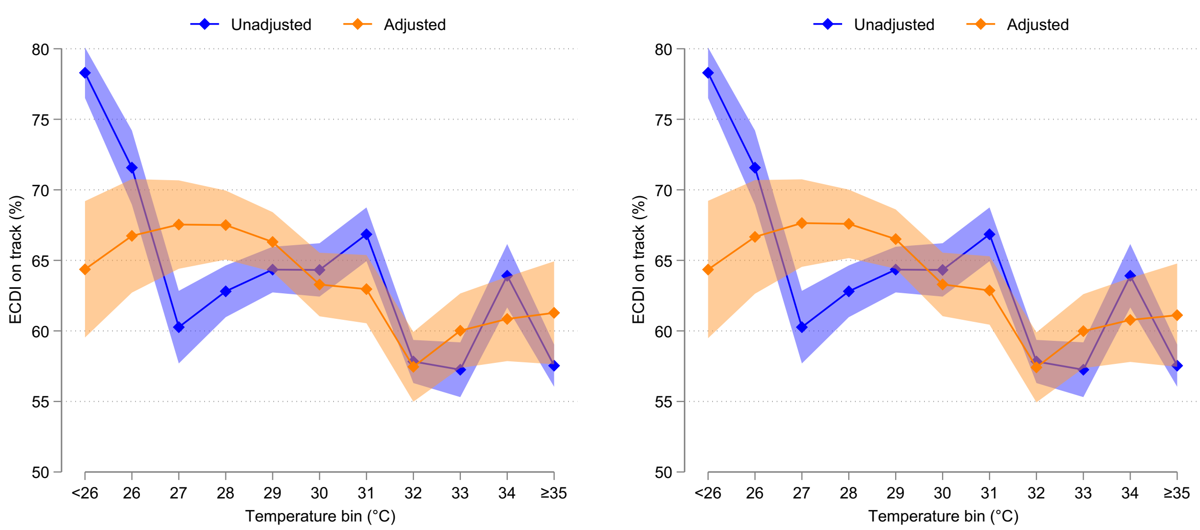
Ambient Heat and Early Childhood Development: A Cross-National Analysis

Supplemental files

Figure S1.

Association between temperature bins and the probability of being developmentally on track: Probit and Logit models

Panel A. Probit Panel B. Logit



Note: The dots represent predicted margins, and the shaded region around the estimates represent 90% confidence intervals from Probit and Logit models for the association between temperature bins and the probability of being developmentally on track as measured by the ECDI. Adjusted model refers to a model adjusting for children's age and sex, maternal education, wealth quartiles, area, dew point temperature and surface pressure, and child birthdate and interview month-year fixed effects and subnational region-country fixed-effects.

Table S2.

Sensitivity check - marginal effects for the association between in-utero exposure to different temperature bins and the probability of being developmentally on track

Temperature bins (°C)	Pregnancy (9 months before birth)	Disaggregated by trimester of pregnancy		
		1st	2nd	3rd
<26 (reference)				
26	0.003	0.047**	-0.010	0.006
	(0.026)	(0.020)	(0.021)	(0.020)
27	-0.013	0.033*	-0.011	-0.009
	(0.026)	(0.018)	(0.020)	(0.019)
28	0.018	0.027	0.029	0.008
	(0.027)	(0.017)	(0.018)	(0.018)
29	0.027	-0.018	0.014	0.002
	(0.027)	(0.017)	(0.018)	(0.018)
30	-0.014	0.008	0.008	0.009
	(0.028)	(0.017)	(0.018)	(0.018)
31	-0.029	-0.001	0.006	-0.026
	(0.030)	(0.018)	(0.019)	(0.019)
32	-0.035	-0.018	0.008	-0.012
	(0.031)	(0.019)	(0.020)	(0.019)
33	-0.019	-0.035*	-0.004	-0.023
	(0.031)	(0.020)	(0.020)	(0.020)
34	0.002	-0.010	0.007	-0.042**
	(0.033)	(0.021)	(0.021)	(0.020)
≥35	-0.023	-0.019	-0.004	-0.009
	(0.035)	(0.018)	(0.018)	(0.018)
N	19,607	19,607	19,607	19,607
Clusters	3,646	3,646	3,646	3,646

Note. The table presents estimates from linear probability models, with corresponding country-cluster clustered standard errors in parentheses. All coefficients were estimated adjusting for children's age and sex, maternal education, wealth quartiles, area, dew point temperature and surface pressure, and child birthdate and interview month-year fixed effects and subnational region-country fixed-effects. *p < .05; **p < .01

Response to the Editor

> *I have therefore decided to offer you the option of submitting a revision, and my interim decision is one of "Not accepted – opportunity to revise and submit a revision". The matters to be addressed before the paper can be re-considered are set out in detail in the referee's reports. I would like to highlight the following particular points:*
> *1. Both reviewers note that exposure during pregnancy also has plausible reasons for expecting impact. Including this period would increase the value of the work.*
> *2. Mechanisms that make impact plausible should be discussed already in the Introduction*
> *3. Reviewers agrees that the rationale for the choice of countries should be made explicit so it can be evaluated for its merit.*
> *4. Country differences should be taken into account more*
> *5. Inconsistencies in temperature cutoffs should be addressed*

Response: Thank you very much for the comments and the opportunity to revise our manuscript for publication in the *Journal of Child Psychology and Psychiatry*. We have used the reviewers' thoughtful and constructive feedback to make substantial edits to the manuscript, which we believe have greatly improved the paper. We also appreciate your clear guidance on the five key points to address, all of which we have incorporated into our revisions. Further updates to the manuscript are detailed below.

Response to Referee #1

1. *The study claims that increased levels of average heat exposure in the first years of life reduce the early childhood development index (ECDI) as illustrated in Fig. 4. However, it is not unlikely that the differences are not only related to temperature, but also differences in countries. After all, temperatures are different between the six countries (Fig. 2). The authors should take this into account and reconsider their conclusion. Please consider to determine the relation between temperature and ECDI for every country.*

Response: Thank you for raising this important point. We have addressed your comment by substantially revising several sections of the manuscript to clarify that our analyses are designed to restrict comparisons within the same country, thereby minimizing cross-country differences unrelated to temperature and mitigating confounding.

Specifically, we now explicitly state throughout the manuscript that our models include subnational region–by–country fixed effects, ensuring consistent terminology. This approach allows us to compare children living in the same country and the same subnational region, rather than across countries, thus avoidinsg potential biases arising from differences in social, economic, or cultural characteristics, as you correctly noted. By including these fixed effects, we effectively control for unobserved heterogeneity at the subnational level, strengthening the internal validity of our estimates. Additionally, we adjust the standard errors by employing clustered standard errors, defined by unique cross-sample cluster MICS identifiers, as recommended in the literature to account for spatial variance differences.

Please refer to our responses to comments 16, 35, and 36 for further details and specific edits.

1. *The authors should explain the rationale for the choice of countries. Also, Fig. 1 shows Laos and Kosovo as well, which are not included in the analysis.*

Response: In response to this comment, we have clarified that the selection of these six countries was based on data availability. Specifically, UNICEF has only recently (2021) granted access to geocoded data for a subset of surveys, and these six were the only ones that included both geolocated data and child development information as measured by the ECDI. We have added the following clarification on page 8: "We selected these countries because they were the only ones with available data on both geolocated household clusters, that is, geographic coordinates for each cluster, and child development, as measured by the Early Childhood Development Index (ECDI)."

We also thank you for noticing that we incorrectly included Laos and Kosovo in our Figure. We have updated it to reflect the analytic sample of the current paper.

2. *We miss a reference to https://urldefense.proofpoint.com/v2/url?u=https-3A__www.unicef.org_reports_state-2Dof-2Dworlds-2Dchildren_2024-23downloads&d=DwIFaQ&c=slrrB7dE8n7gBJbeO0g-IQ&r=3zqEnj4EVtl1LmdmTKbQ96oMe5F9CAMbhcL3pr9UHkY&m=uawOgjah9P0J9aufrqDNtr2GniKvR3irs4-nCvkMpmuPmOGvwuoy1t4oazwzRXOW&s=uuBqa5Uq9cY8BrVlZU2XE9RvlEbZDlwhPawn4BDmvwQ&e= . It may replace the UNICEF 2005 reference.*

Response: Thank you for the suggestion. We have included the recommended reference and have also retained the UNICEF (2005) citation, as it documents the development and implementation of the Multiple Indicator Cluster Survey.

3. *The average temperature that the children are exposed to from birth to interview is taken as the independent variable. No other parameters, such as maximum temperature, heat waves days or heat indices including humidity and solar radiation are discussed. It would be nice to add this to the discussion or provide a clear rationale for average temperature as independent variable.*

Response: We made three significant additions in response to this comment. First, we clarified throughout the manuscript that our independent variable is 'exposure to monthly maximum average temperature,' rather than simply 'average temperature.' Second, we now reference relevant literature informing our decision to use maximum average temperature to operationalize heat exposure: "Within these buffers, we followed related literature (Aguilar-Gomez et al., 2024; Deschenes, 2014) and extracted and averaged the climate variables for each buffer by month for each child, specifically calculating the mean monthly maximum temperature that children were exposed to from birth to the interview date." (page 10)

Third, we appreciate the observation that heat exposure can be conceptualized in various ways, such as through the number of heatwave days, heat indices, and other metrics. We agree that it is important to critically reflect on the choice of indicator and to acknowledge the lack of a universally agreed-upon measure for heat exposure, as highlighted in the recent systematic review by Brimicombe (2024). To enhance transparency and provide a more nuanced discussion, we have included the following addition in the manuscript: "Second, we operationalized heat exposure as the mean monthly maximum temperature, aligning with much of the existing literature that uses average temperatures to capture the cumulative intensity of heat exposure (Aguilar-Gomez et al., 2024; Deschenes, 2014). However, alternative approaches exist—for example, measuring the number of days exceeding a specific temperature threshold (e.g., Park et al., 2021), and there is currently no consensus in the field on the most appropriate way to conceptualize and operationalize heat exposure when studying its impacts on human health and development (Chloe et al., 2024)." (see page 19)

4. *Abstract. Please consider to explain what the sixth round means- maybe use 'most recent' instead of sixth round.*

Response: Thank you for this suggestion. In response, we edited this sentence as follow: "The sample comprised 19,607 children aged three and four from Georgia, The Gambia, Madagascar, Malawi, Sierra Leone, and The State of Palestine, all participants in Multiple Indicators Cluster Surveys collected between 2017 and 2020"

5. *Introduction The authors explain (P6L11 onwards) that research regarding effects of temperature on childhood development contains many confounders, but they do not explain how this study is not compromised by these confounders*

Response: In response to this comment, we revised the final paragraph of the Introduction to directly address how the study mitigates selection bias and accounts for potential confounding from the factors mentioned. Specifically, we now state the following: "This study addresses these gaps in the literature by studying the effects of excessive ambient heat on early childhood development skills in six countries. Following work in environmental economics (e.g., Deschenes, 2014), we mitigate concerns about selection bias by linking geocoded data on children with high-resolution longitudinal temperature data. Specifically, our approach allows for comparisons among children living within the same subnational region, thereby reducing concerns about systematic differences in climatic, economic, or social conditions across regions, while also accounting for seasonality effects." (page 7)

6. *Methods P8L6 change 'ECDILoizillon' to ''ECDI) (Loizillon'*

Response: Thank you for noticing this typo. We have fixed it.

7. *P9L8 What is the difference between 'atmospheric moisture content' and 'air humidity'? Consider to add units.*

Response: In response to this comment, we clarified the definition and operationalization of dew point temperature in our analyses in page 10. In our analysis, we use the dew point temperature from the ERA5 dataset, which represents the temperature at which air becomes saturated with moisture and condensation begins, assuming constant pressure. It is expressed in Kelvin (K) in ERA5, and we converted to degrees Celsius by subtracting 273.15. Unlike relative humidity, dew point provides an absolute measure of atmospheric moisture, closely related to the actual water vapor content in the air. This distinction is important because the dew point is not affected by temperature fluctuations in the same way as relative humidity. In the context of heat and thermal stress, higher dew point temperatures indicate more humid conditions, which reduce the body's ability to cool itself through evaporation (sweating), thereby increasing the perceived temperature and contributing to greater heat-related health risks.

8. *The explanation of the model (P9L42 onwards) is hard to understand. Please consider to explain in more detail.*

Response: We substantially revised the Analytic Approach section in response to this comment, which we believe significantly improved the clarity and coherence of the section (see pages 10-12)

9. *What is the geographical size of the clusters? And how does this relate to the temperature estimated, as weather data used has a spatial resolution of approx. 9 kilometers?*

Response: Thank you for this thoughtful question. To clarify what clusters are, and their approximate size, we have edited the text as follows: "Households are selected using probability proportional to size sampling within clusters, which correspond to the primary sampling units and typically include 20-25 geographically proximate households, often within a single census enumeration area" (page 8). Indeed, while the exact geographic size of clusters varies by context, they generally represent small, localized communities of 20 to 25 households.

Regarding the weather data, the ERA5 has a spatial resolution of approximately 9x9 kilometers, which is currently the most granular global weather dataset with consistent coverage across time and space. Although this resolution is coarser than the likely size of most MICS clusters, we believe it is appropriate for several reasons. First, as described on page 8, MICS cluster coordinates are intentionally displaced (up to 2 km in urban areas and up to 5 km in rural areas) to protect respondent anonymity. This displacement limits the value of using higher-resolution weather data, as the precise location of each cluster is inherently uncertain. Second, to mitigate potential mismatch between cluster location and weather grid points, we average temperature across all ERA5 grid cells intersecting each displaced cluster location, which provides a robust estimate of local conditions while reducing noise introduced by misalignment. Finally, using higher-resolution temperature data, if available, would introduce significant computational burdens and potentially greater measurement error due to location uncertainty. As such, the 9 km resolution represents a reasonable trade-off between spatial precision and data reliability.

We have clarified these methodological choices in the revised manuscript, and we appreciate the opportunity to elaborate on this point.

10. *Results: A comparison is made between 26 °C (or lower) and 32°C (or higher) in an inconsistent manner (e.g. sometimes 26, sometimes 26 or lower). Why are those two temperatures selected and how can we see or calculate from figure 3 what percentage points are?*

Response: We have revised the manuscript in response to this comment. First, in our main binned temperature specifications, we selected temperatures below 26°C as the reference category for two key reasons: (1) existing evidence suggests that temperatures above 26°C may be associated with adverse mental health and behavioral outcomes, and (2) the distribution of temperature in our sample, selecting a lower threshold would have resulted in too few observations in the reference group. For similar reasons, we chose to group all temperatures above 32°C into a single upper category. Accordingly, we have edited the text throughout the manuscript to consistently refer to “below 26°C” as the reference point. In addition, we have clarified the rationale for these threshold choices on page 11, as follows: “[…] using exposure to average maximum temperatures below 26°C as the reference category (i.e., temperature bins). This threshold was informed by evidence suggesting potential adverse effects of temperatures above 26°C on mental health and behavior (Evans, 2019; Thompson et al., 2023) as well as the temperature distribution in the current sample.”

Furthermore, to assess whether the choice of below 26°C and above 32°C as thresholds might be driving our results, we conducted a sensitivity check using a binscatter least squares estimation. This analysis supports the robustness of our findings. We now describe this sensitivity check in greater detail in the revised manuscript (pages 11-12): “First, although the selection of 26°C as the reference category in our binned specification was informed by prior evidence, we also conducted a binscatter least squares estimation as a sensitivity check. In this approach, the continuous temperature variable is divided into intervals (or bins), and each point in the plot represents the average ECDI score within a temperature bin, plotted against the average temperature in that bin, allowing us to visualize the underlying functional relationship while smoothing out noise.”

11. *Table 2: interesting that for the socio-emotional domain significant results are observed at temperatures of 32 °C and not higher. Please explain in the discussion.*

Response: In response to this comment and comment #17, we have included one additional paragraph in the discussion section on the socio-emotional and physical domains (page 17): “Conceptually, the same mechanisms linking excessive heat with cognitive outcomes could also affect children's physical and social-emotional development. However, in our sample, the evidence for such associations was less consistent. We found a statistically significant association between temperatures of 32 °C and a lower likelihood of being developmentally on track in the socio-emotional domain, but not at higher temperatures. This inconsistent pattern may reflect measurement limitations in socio-emotional development relative to the literacy-numeracy domain, as noted in prior research (McCoy et al., 2016). Similarly, we observed a positive association between temperatures of 26 °C and physical development, relative to cooler days, but again no consistent effects at higher temperatures. These mixed findings suggest caution in interpreting the effects of heat on physical and socio-emotional development in this sample. It is also possible that the effects of early-life heat exposure emerge more clearly in cognitive outcomes during early childhood, with impacts on other domains, such as socio-emotional functioning becoming evident only later in life. Future studies using more precise measures and longitudinal designs are needed to clarify these patterns.”

12. *Table 3: Significant results are shown for temperatures of 32 and higher. In the conclusion and key points, 30 or higher is claimed. Please correct.*

Response: Thank you for your comment. We acknowledge that setting 30 as the threshold was sometimes inaccurate, as you noted. We've corrected this but still use temperatures above 30 to help define impact ranges in certain cases.

13. *In Table 3 no differences are observed for the unadjusted model between probit and logit. Therefore consider not to duplicate these values. For the adjusted model, minimal differences are observed only for the lowest and highest temperature bin. Is it therefore worthwhile to make this distinction between the probit and logit model?*

Response: We made two edits in response to this comment. First, given that these results are sensitivity checks, and not central to the manuscript (as the results presented in Table 2 and the Figures), we decided to move the table to the supplemental files and switch the presentation to make it easier for the reader to compare with Figure 3 (see now Figure S1 depicting predicted margins as in Figure 2). Second, we now describe the rationale for the inclusion of these sensitivity checks (page 12): "Second, we estimated probit and logistic regression models instead of linear probability models, which account for the bounded nature of binary outcomes and allow for nonlinear relationships between the predictors and the probability of the outcome, providing a useful check on whether our findings are sensitive to the functional form of the model and distributional assumptions.

14. *Discussion. The possible explanations provided for reduction of childhood development with higher temperatures include diseases, food supply, and aggression. However, please consider to include work that makes a direct link between heat and mental performance, such as Piil J.F., Christiansen L., Morris N.B., Mikkelsen C.J., Ioannou L.G., Flouris A.D., Lundbye-Jensen J., Nybo L. Direct exposure of the head to solar heat radiation impairs motor-cognitive performance (2020) Scientific Reports, 10 (1), art. no. 7812*

Response: Thank you for this suggestion. We have included a reference to Piil et al (2022) on page 17.

15. *Heat strain prior to birth is important for the development of children as well. Consider to refer to (Brink et al., 2024). Please also discuss if the first 1000 days may be more appropriate; it is well recognized as a critical period for growth and development.*

Response: Thank you for these suggestions. In response, we have included references to Black 2017 and Draper 2025 to demonstrate importance of the "first 1000 days" and the "next 1000 days," as well as to Brink et al (2024) to discuss the importance of prenatal exposure to heat.

16. *How do you ensure you're not comparing contexts that are very different (e.g. average maximum temperatures in Georgia and The Gambia differ a lot – maybe in-country analysis would be interesting, because there is no 30+ cluster in Georgia for instance)*

Response: Thank you very much for this important comment. In response, we have edited the text to clarify that we have included region-country fixed-effects, meaning that we are "comparing" children living in the same country and the same sub-national region. Specifically, now we describe the fixed-effects as follows: "In the model, $\boldsymbol{X}_i$ was a set of covariates (children's age and sex, maternal education, wealth quartiles, area, dew point temperature and surface pressure, and child birthdate), and γ_g and ρ_t denoted subnational region-country fixed effects and month-year fixed effects, respectively. These fixed effects allowed us to control for seasonality effects and restrict comparisons between children within the same country and same subnational region who were exposed to different average maximum temperatures due to temporal variation in temperature levels relative to their birthdates and interview dates." (page 11)

Additionally, we clarified in other sections of the manuscript, including the discussion, that our comparisons are restricted to children within the same subnational region, rather than across countries, such as comparing children from Georgia and Gambia, e.g.: "We found that children exposed to monthly average maximum temperatures above 30°C were less likely to be developmentally on track compared to those exposed to cooler temperatures. This association was consistent even after controlling for baseline average climatic conditions, by comparing children in the same subnational region and adjusting for seasonality effects, as well as other individual and contextual factors." (page 16)

17. *The discussion lacks information on significant differences in the four other ECDI domains.*

Response: We have edited the manuscript to respond to this comment. Please see our response to comment #11 for details.

18. *Tables and figures. The legend of Table 1 is incomplete. Maternal education does not add up to 100%. Why are there two decimals if the last number is always zero?*

Response: Thank you. We have fixed the Table and decided to keep only one decimal.

19. *Please reconsider the legends for all figures, they are too short to understand the figure.*

Response: We have revised all figure legends and added additional details to improve clarity and facilitate interpretation.

20. *The percentages mentioned for the child development are only for on track. Is it correct to assume that 37.1% is not on track for ECDI? If yes, please consider to mention this more clearly.*

Response: Thank you for this suggestion. In response, we have clarified as follow: "In the analytic sample, almost 63% of children were developmentally on track and 37% not on track according to the ECDI."

21. *Table 2 and 3 What are the units? What are the values between parenthesis?*

Response: We have clarified in the Table footnote, describing the coefficients and standard errors.

22. *Figure 2, 3, 4 and 5 Units (°C) are missing on the horizontal axis*

Response: Thank you. All figures and tables now display units clearly.

23. *Figure 3. What exactly is a precited margin. Is this the coefficient from the linear probability model?*

Response: Predicted margins are not the coefficients from the linear probability model; rather, they are model-based predicted probabilities of the outcome at specific values of the independent variable, averaging over the distribution of covariates. To clarify, we have included the following: "The Figure presents predicted margins (i.e., model-based predicted probabilities of the outcome at specific values of the independent variable) for the unadjusted model which does not include any covariates, and for the model including all covariates and geographic and temporal fixed effects." (see page 12)

24. Figure 3 'Unadjusted' (L43) likely has to be 'adjusted'

Response: That's correct—thank you for catching this typo. It has been corrected.

25. Figure 4 Where do the 28 points come from?

Response: Thank you for this question. We have revised the manuscript to clarify and improve the interpretation of our results. First, in the Methods section, we now describe the rationale for the binscatter least squares estimation as follows (see pages 11-12): "First, although the selection of 26°C as the reference category in our binned specification was informed by prior evidence, we also conducted a binscatter least squares estimation as a sensitivity check. In this approach, the continuous temperature variable is divided into intervals (or bins), and each point in the plot represents the average ECDI score within a temperature bin, plotted against the average temperature in that bin, allowing us to visualize the underlying functional relationship while smoothing out noise."

Second, we added the following explanation to the footnote of Figure 4 to clarify what the 28 points represent: "Each dot represents the average ECDI score for observations within a temperature bin, plotted against the average temperature in that bin."

26. Figure 5 has no horizontal axis.

Response: Thank you. In response to this comment and the feedback in Comment 22, the issues with axis labels, titles, and units have been addressed.

27. Please consider to make the dataset available to the reader of the paper.

Response: Unfortunately, our agreement with UNICEF regarding access to the GIS data does not permit public sharing. Therefore, we now direct readers to the MICS website for data access, as follow: "The MICS and climate data used in this study are publicly available. Geocoded information from the MICS can be obtained upon request from the survey developers (mics.unicef.org)." (page 8)

28. References: Reference of Evans is incomplete

Response: We have fixed the reference.

29. Reference of Romanello has misspellings

Response: We have fixed the reference

Response to Referee 2:

30. The manuscript covers the important and understudied issue of the effects of heat exposure on ECD. The authors find that higher ambient temperatures are associated with *poorer ECD outcomes. The paper is well-written and methods appropriate. The questions posed and results presented are very relevant.*

Response: Thank you very much for the positive comments and helpful feedback

31. *MAJOR COMMENTS: The paper can benefit from a more detailed explanation of the mechanisms/pathways through which heat affects ECD. Some of these are mentioned in the Discussion, but brining them up earlier would be helpful particularly for readers not too familiar with the topic.*

Response: We agree and have added a more detailed explanation of the mechanisms through which heat can affect early childhood development in the introduction. Specifically, we now describe the following mechanism on page 5:

"However, there is little evidence on how exposure to excessive ambient heat early in life, which is a sensitive period of brain development, may affect the development of foundational skills (Cuartas et al., 2024; Draper et al., 2024; Herbst, 2024). High ambient temperatures may affect early childhood development by causing dehydration, neuroinflammation, heightened activation of the stress response system, and disrupted sleep (Berger et al., 2023; Sorensen & Hess, 2022; Walter & Carraretto, 2016; White et al., 2007; Yan et al., 2023). Young children are particularly vulnerable to ambient temperatures given their heightened sensitivity to environmental input, their under-developed biological systems, which are less capable of regulating and releasing heat via sweating, and their dependence on adults to seek water or cooler environments (Early Childhood Scientific Council on Equity and the Environment, 2023).

Excessive ambient heat can also influence young children's development through broader ecological mechanisms. For example, extreme heat can damage crops, increase the risk of food contamination, and promote the spread of disease vectors such as mosquitoes, all of which threaten children's health and nutrition, essential foundations for healthy development (Draper et al., 2024; Kemp et al., 2022; Schlenker & Roberts, 2009). Additionally, the well-documented effects of heat on mental health may impair parenting and reduce the quality of caregiver–child interactions, both of which are critical for the development of cognitive and socio-emotional skills (Bornstein, 2015; Cuartas et al., 2024). Excessive heat may also limit children's exposure to learning opportunities by making outdoor environments less safe and contributing to more sedentary behavior (Koepp et al., 2023). Consequently, understanding the developmental effects of early exposure to heat remains critical, especially considering that over one third of children around the world are highly exposed to heatwaves and almost every child on earth is already experiencing the downstream consequences of climate change (Rees, 2021)."

32. *An implicit assumption is that the entire period from birth to interview matters for the effect of heat on ECD. What is the evidence that effects of heat are cumulative? Given the brain's plasticity in early life, assuming cumulative effects may be a stretch. What is the evidence that in utero exposure to heat does not matter for ECD? Have you considered running a sensitivity analyses for the entire period from conception*

Response: We appreciate this insightful suggestion and have addressed it in the revised manuscript. Specifically, we conducted a sensitivity analysis examining exposure from conception to birth, as well as by pregnancy trimester. As individual pregnancy lengths were not available, we assumed a standard nine-month duration across the sample. The results are presented in the supplemental materials (Table S2) and are discussed in the main text., Page 14:

"Finally, while the main goal of this study was to assess the potential effects of excessive heat exposure from birth to the MICS interview date, extensive evidence also indicates that in-utero exposure to excessive heat can negatively impact human development outcomes (Brink et al., 2024). Consequently, we conducted a sensitivity analysis to examine the association between prenatal exposure to excessive heat and being developmentally on track (ECDI), assuming an average pregnancy duration of nine months. Our results, presented in Table S2 (supplemental files), show somewhat inconsistent association between temperature bins and the ECDI. We observed statistically significant associations between temperatures of 26°C and 27°C in the first trimester of pregnancy and a 4.1 (SE=0.020) and 3.3 (SE=0.018) percentage points higher likelihood of being developmentally on track, as well as between temperatures of 33°C and a 3.5 percentage points (SE=0.020) lower probability of ECDI on-track, relative to temperatures below 26°C. Moreover, temperatures of 34°C in the third trimester were associated to a 4.2 lower likelihood (SE=0.020) of being developmentally on track relative to temperatures below 26°C. These results align with recent evidence on how heat can exacerbate risks for neurodevelopment early and late in pregnancy (Lin et al., 2025)."

33. *Another implicit assumption is that children lived in the same cluster their entire life. You are assigning lifetime heat exposure based on where children lived at the time of the interview. They may have lived in this community their entire life or only moved recently. This issue doesn't come up until the limitations section (page 15, lines 26-31). I think it should be noted earlier to put results into perspective.*

Response: This is an excellent point, and we have revised the manuscript accordingly. Specifically, we have now included the following clarification in the Methods section (page 10): "Due to the absence of residential history data in MICS, we assign temperature exposure based on the child's current cluster of residence, implicitly assuming residential stability from birth through the time of the survey."

34. *Methods: It's not entirely clear from the text why temperatures below 26 and above 34 were grouped together in the results.*

Response: Thank you for this comment; we have revised the manuscript in response to it. First, in our main binned temperature specifications, we selected temperatures below 26°C as the reference category for two key reasons: (1) existing evidence suggests that temperatures above 26°C may be associated with adverse mental health and behavioral outcomes, and (2) the distribution of temperature in our sample, selecting a lower threshold would have resulted in too few observations in the reference group. For similar reasons, we chose to group all temperatures above 32°C into a single upper category. Accordingly, we have edited the text throughout the manuscript to consistently refer to "below 26°C" as the reference point. In addition, we have clarified the rationale for these threshold choices on page 11, as follows: "[…] using exposure to average maximum temperatures below 26°C as the reference category (i.e., temperature bins). This threshold was informed by evidence suggesting potential adverse effects of temperatures above 26°C on mental health and behavior (Evans, 2019; Thompson et al., 2023) as well as the temperature distribution in the current sample."

Furthermore, to assess whether the choice of below 26°C and above 32°C as thresholds might be driving our results, we conducted a sensitivity check using a data-driven binscatter least squares estimation. This analysis supports the robustness of our findings. We now describe this sensitivity check in greater detail in the revised manuscript (page 11-12): "First, although the selection of 26°C as the reference category in our binned specification was informed by prior evidence, we also conducted a data-driven binscatter least squares estimation as a sensitivity check. In this approach, the continuous temperature variable is divided into intervals (or bins), and each point in the plot represents the average ECDI score within a temperature bin, plotted against the average temperature in that bin, allowing us to visualize the underlying functional relationship while smoothing out noise."

35. *It's not entirely clear how the data were pooled from each country and why there are no country fixed effects. The six countries are in very different agro-ecological and climatic zones to warrant inclusion of country fixed effects in addition to within-country geographic fixed effects.*

Response: Thank you very much for this important comment. We have edited the text to clarify that we have included region-country fixed-effects, i.e., we are comparing children living in the same country and the same sub-national region. Specifically, now we describe the fixed-effects as follows: "In the model, $\boldsymbol{X}_i$ was a vector of covariates (i.e., age, education, wealth, etc.), and γ_g and ρ_d denoted region-country fixed effects and month-year fixed effects, respectively. These fixed effects allowed us to control for seasonality effects and restrict comparisons between children within the same country and same sub-national region who were exposed to different average maximum temperatures due to temporal variation in temperature levels relative to their birthdates and interview dates."

36. *Can you please clarify the geographic fixed effects you included? Parts of the text indicate province or municipality fixed effects, whereas other parts indicate region fixed effects.*

Response: In response to this comment, we have clarified that we refer to subnational region by country fixed effects throughout the document. To avoid any confusion, we now consistently refer to them as "subnational region–by–country fixed effects."

37. *Can you please clarify the unadjusted and adjusted models in the methods, not just the tables and figure 3? Fig 3 defines the unadjusted models (but not the adjusted) as the model including everything, which seems inaccurate and differs from the text. What was included in the unadjusted model?*

Response: Thank you for raising this important point. As noted in our response to the Comment #25, we had a typo on the Figure 3 legend and it should say "adjusted" instead of "unadjusted." Additionally, we added the following sentence at the beginning of the Results section to clarify the distinction between the unadjusted and adjusted models: "The Figure presents predicted margins for the unadjusted model, which does not include any covariates, and for the model including all covariates and geographic and temporal fixed effects." (page 12)

38. *How was missing data handled? Having worked with MICS data I find it hard to believe there was no missing data on any of the variables considered in the analysis, unless a complete case analysis was conducted. Please clarify.*

Response: We clarified in the Methods section that we employed a complete case analysis. (page 9)

39. *Heterogeneity analyses: Why were these specific modifiers tested? While I agree with you that understanding compounding risk factors is important, there needs to be clear rationale why these specific risk factors were tested and not others. What are the mechanisms/pathways through which these risk factors compound the effects of heat on ECD?*

Response: Thank you for raising this important point. In response, we have added a new paragraph to the introduction that outlines the rationale for selecting these specific factors in the moderation analysis (page 7): "Furthermore, we examined whether the effects of ambient heat on child development varied between wealth groups, urban versus rural settings, and household with and without access to adequate water and sanitation. These factors were selected as potential moderators because they may either mitigate or exacerbate the risks associated with excessive heat (Balza et al., 2025; Romanello et al., 2024) – for example, by providing resources to cope with heat (such as access to clean water) or by amplifying exposure and related risks (such as increased heat concentration in urban areas or contamination in households lacking adequate sanitation). Finally, given the unequal distribution of vulnerability to and gender-differentiated impact of different climate hazards (Awiti, 2022), we conducted an exploratory analysis to assess whether the effects of ambient heat differed between boys and girls."

40. *Fig 5D, what is the purpose of testing both the improved and unimproved indicators? Isn't improved water just the opposite of unimproved water? Were these estimated using your preferred adjusted linear probability model?*

Response: Thank you for this observation. We estimated moderation models using a binary indicator for improved versus unimproved water and then calculated predicted margins from our adjusted linear probability model. These margins reflect the estimated probability of the outcome for each category, holding all other covariates constant. While the indicator is binary, presenting predicted margins for both values (improved and unimproved) is standard practice when presenting predicted margins and enhances interpretability allows us to clearly illustrate differences in predicted probabilities across water source types, based on the same underlying model.

41. *How exactly can clean water and sanitation buffer the effects of heat (page 15)? further explanation of the specific mechanisms through which clean water can mitigate effects of heat on ECD would be helpful.*

Response: Thank you for highlighting this important point. In response to your feedback, we made two key revisions.

First, we added a paragraph to the introduction outlining the rationale for including the selected moderators, along with a brief description of the potential pathways through which they may exert influence (see page 7): "Furthermore, we examined whether the effects of ambient heat on child development varied between wealth groups, urban versus rural settings, and household with and without access to adequate water and sanitation. These factors were selected as potential moderators because they may either mitigate or exacerbate the risks associated with excessive heat (Balza et al., 2025; Romanello et al., 2024) – for example, by providing resources to cope with heat (such as access to clean water) or by amplifying exposure and related risks (such as increased heat concentration in urban areas or contamination in households lacking adequate sanitation). Finally, given the unequal distribution of vulnerability to and gender-differentiated impact of different climate hazards (Awiti, 2022), we conducted an exploratory analysis to assess whether the effects of ambient heat differed between boys and girls".

Second, we expanded the discussion section to clarify how and why access to adequate water and sanitation may function as a moderating factor. (page 18): "Furthermore, combined with inadequate access to water, which was found to be a significant moderator, heat exacerbates the risks of water scarcity, contamination, and disease transmission. Exposure to pollutants and contamination during early childhood can disrupt synapse development in key brain areas, thereby impairing children's cognitive and social-emotional developments (Walker et al., 2011). Conversely, access to adequate water can act as a protective buffer against the detrimental effects of heat on children by offering a readily available means of cooling"

42. *How exactly should low SES communities be supported (page 14)? What about households in urban areas? Why test modifiers without further discussing the implications.*

Response: Thank you for this thoughtful suggestion. In response, we added a paragraph discussing more specific policy implications (page 18): "Findings from the heterogeneity analyses highlight the urgent need to prioritize support for economically disadvantaged communities in efforts to mitigate heat-related risks to early childhood development. A critical area of investment, as suggested by the current results, is the provision of reliable water and sanitation infrastructure, which can offer opportunities for cooling and reduce exposure to heat-related contaminants. Additional supports may include cash transfer programs, which can enhance families' ability to access resources needed to cope with extreme heat, and the distribution of cooling tools, such as fans. Furthermore, the finding that heat effects are more pronounced in urban compared to rural areas, consistent with the urban heat island effect, underscores the importance of ecological and infrastructure-based interventions, including increasing vegetation cover, implementing cool surface technologies, and enhancing urban infrastructure to support temperature regulation."

43. *Overall, the heterogeneity analyses are interesting and provide much basis for future research and discussion. However, they appear exploratory and largely opportunistic, based on available data. This should be more clearly explained in the text.*

Response: Thank you for this comment. As noted in our response to comment #39, we have provided a rationale for the heterogeneity analyses and the selected moderators, and clarified that the analysis of sex differences was entirely exploratory.

44. *MINOR COMMENTS: While I agree with you about the limitations of ECDI, your statement that future research should use direct assessments needs a bit more nuance (page 15, lines47-50). Heat at the time of assessment can affect performance on an ECD assessment, e.g., the child can be tired, unmotivated, sleepy, etc. This is in fact alleviated when using a parent-reported tool. It would be worth highlighting some of these nuances for future researchers considering examining the relationship between heat and ECD.*

Response: Thank you for raising this important point. In response, we include the following clarification in the limitations section: "Third, the ECDI used in this study is a parent-reported, limited-in-scope measure of child development with relatively low precision, which introduces uncertainty into the point estimates and coefficient attenuation. Additionally, heat exposure can make children tired, unmotivated, or sleepy, potentially affecting their performance on direct assessments of early childhood development. This raises concerns about endogeneity in the measurement of developmental outcomes. Future research should account for these nuances by employing multi-method assessment approaches that combine both direct assessments and parent reports to more reliably capture the developmental impacts of excessive heat." (pages 19-20)

45. *Text goes back and forth between "global warming" and "climate change". Please stick to the latter as the more accurate term.*

Response: In response to this comment, we now refer to "climate change" consistently throughout the manuscript

46. *The abstract does not define the primary outcome*

Response: We have included a mention to the primary outcome, as follows: "Our primary outcome is the Early Childhood Development Index (ECDI)."

47. *The text goes back and forth between disadvantaged households, low-SES households, socio-economically disadvantaged households. Please use one term consistently, unless there is a difference in definitions.*

Response: In response to this comment, we now refer to "economically disadvantaged" consistently throughout the manuscript

48. *The relevance statement, line 10, says less attention has been given to how heat affects young children. While certainly true about ECD, it's less true about other outcomes as you describe in the intro and discussion.*

Response: we agree with your observation and have revised the text accordingly: 'While much is known about the broader impacts of climate change, less attention has been given to how high temperatures affect young children's development.

49. *Figure 1 – what are the black clusters in the Balkans and South East Asia? There were no countries included from these regions.*

Response: Apologies for the oversight - the earlier version of the map was based on an outdated file that included countries ultimately excluded from the analysis due to lack of relevant data. We have updated the figure to reflect only the final analytic sample.