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Original Contribution

Health disparities in the impact of prenatal rainfall variation on child growth: quasi-experimental evidence from Peru

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Abstract

Climate variability increasingly impacts population health, with pregnant people and children among the most at risk. This study examines how prenatal rainfall variation influences child growth in Peru and how these associations differ across climatic zones and socioeconomic groups. By focusing on health disparities in early life, it contributes to the literature on climate variability and health in Latin America. We use a quasi-experimental design linking seven rounds of the Peru Demographic and Health Surveys (DHS, 1996-2012) with region-level rainfall data ($n = 64\,859$ children, < 5 years). We find that excess rainfall during pregnancy reduces children's height-for-age *z*-score (−0.073; 95% confidence interval [CI], −0.112 to −0.035) and increases the odds of stunting (1.139; 95% CI, 1.064 to 1.220). Stronger impacts of more rainfall than usual are observed among rural populations and children whose mothers did not complete formal education. Particularly in the coastal region, rainfall deficits are associated with improved height-for-age z-scores (0.029; 95% CI, 0.002 to 0.056), highlighting the role of climatic contexts. These findings underscore that climatic variations, such as rainfall variations, do not affect all populations equally. By documenting such disparities, this study provides evidence on the intersection of climate variability, health, and inequality in Latin America and points to the need for context-sensitive research and targeted interventions in climate-sensitive regions, such as the Andes and Amazon.

This article is part of a Special Collection on Latino Health.

Key words climate change, cohort studies, disparities (health disparities), environmental epidemiology, global health, natural experiments, pregnancy outcome

Introduction

Height growth in childhood is associated with physical and cognitive health across the life course, with lower height-for-age linked to, e.g., increased risks of cardiovascular and other chronic diseases.[1-3] The literature on the Developmental Origins of Health and Disease has established that child growth is shaped by environmental influences in early life, including nutritional shocks.[4,5] As long-term indicators of malnutrition, height-for-age *z*-scores (HAZ) and stunting are widely used to assess the lasting impacts of adverse prenatal environments.

This study contributes to this literature by studying health disparities in the impact of prenatal rainfall anomalies on height growth among under 5-year-old children in Peru. Rainfall anomalies have recently received increasing attention in the literature on the Developmental Origins of Health and Disease, as they are expected to become more frequent and unpredictable.[6,7] In many low and middle-income settings, this threatens agricultural production and increases the risk of maternal undernutrition during pregnancy, which in turn is associated with impaired child growth.[8,9]

In Latin America, stunting rates remain at intermediate levels at 11.5%.[10] Peru made substantial progress in reducing stunting, from 31.1% in 2000 to 10.1% in 2022.[10] However, a considerable burden persists particularly among socially disadvantaged groups.[11] At the same time, Peru is vulnerable to climate-related hazards due to its dependence on agriculture, social inequalities, and weather phenomena such as El Niño.[12]

While research on climate and health is growing in Latin America, gaps in regional coverage and analytical depth remain.[13,14] Given that environmental stressors such as rainfall anomalies may affect populations differently across social, economic, and geographic contexts, they risk to deepen existing inequities in child health outcomes.[15] Earlier work has documented adverse impacts of rainfall anomalies during pregnancy on height growth among children in various world regions.[5,8,12,16-22] However, the impact of rainfall variation on child

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growth is highly context-specific, and may depend on timing, intensity, and local conditions.[21] Consequently, to achieve the Sustainable Development Goal of ensuring healthy lives for all at all ages, an improved understanding of which vulnerabilities shape health impacts in response to early-life exposure to rainfall anomalies is pivotal.[23,24]

This study uses a quasi-experimental design to address these knowledge gaps by identifying the sources of vulnerability that contribute to health inequities arising from rainfall anomalies during pregnancy in Peru.

Methods

Data

We use seven rounds of the Peruvian Demographic and Health Survey (DHS) (1996, 2000, 2005, 2009-2012) conducted by the Instituto Nacional de Estadística e Información.[25] The DHS applies a stratified, multistage random sampling design and collects information on reproductive, maternal, and child health during household interviews. It also provides anthropometric measurements for children under five taken by trained measurers. We also observe children's place of residence at the regional level (24 regions). The child-level dataset is merged with detailed maternal and household data, yielding a final analytical sample of 64 859 children born between 1991 and 2012.

Outcome measures

The primary outcome is the World Health Organization (WHO)-defined HAZ. As a standardized and widely adopted indicator of chronic child malnutrition, HAZ provides a measurement of long-term growth deficits and enables comparisons across studies.[4,16,26] The DHS provides standardized z-scores according to the WHO child growth standards. Additionally, we construct binary outcome measures where the dependent variables indicate whether a child is stunted (HAZ < -2) or severely stunted (HAZ < -3).

Exposure measures

The exposure measures are calculated using precipitation data from the ERA5 reanalysis dataset obtained from the EU Copernicus Climate Change Service.[27] For each region, we calculate monthly rainfall averages for 1980 to 2012. This period constitutes a historical baseline and includes all potential prenatal exposures for children in the sample. Following Le and Nguyen,[5] prenatal rainfall variation is measured as standardized deviations from historical monthly averages in each region, based on a uniform 9-month window extending from the birth month backwards. For each region and calendar month, we compute the average rainfall in the preceding 9 months and standard deviation. For each child in the sample, we then calculate cumulative rainfall in the 9 months prior to their birth month, subtract the region-specific rainfall mean in the respective 9 months time window prior to that calendar month, and divide by the region-specific standard deviation. This yields a *z*-score measure, allowing comparability across regions by expressing rainfall during an individual's time in utero relative to local climatic norms.

The standardized rainfall deviation is decomposed into two exposure measures to distinguish between positive (excess rainfall) and negative (below-average rainfall) prenatal exposures. This accounts for potential differential impacts of positive and negative rainfall deviations on HAZ. Empirical findings support this differentiation as Le and Nguyen[5] and Abiona[28] observed differential associations for negative and positive rainfall deviations. Operationally, the "positive rainfall deviation" variable equals the region-and-time specific rainfall *z*-score, but is set to zero when the deviation is negative. Conversely, the "negative rainfall deviation" variable equals the absolute value of negative z-scores, ensuring that both measures only take positive values.[5]

Since the impacts on height growth may differ by the intensity of the rainfall deviation[22], we additionally construct binarized exposure variables. Exposure to very high rainfall is defined as a 9-month prenatal period during which average rainfall exceeds the 80th region-specific percentile, while exposure to very low rainfall refers to periods when average rainfall falls below the 20th percentile (droughts). This follows cutoffs used in previous research.[29]

Quasi-experimental empirical strategy

The main challenge when estimating the impacts of rainfall variation on childhood linear growth is that there may be systematic differences between children growing up in generally drier versus generally wetter regions. To address this potential source of confounding, we employ a quasi-experimental identification strategy that utilizes the quasi-random nature of rainfall patterns within regions. For this, we use the deviation between the expected and the actual rainfall for the 9 months before a child's birth. The expected rainfall is calculated based on long-term region-specific means for specific calendar months. The intuition is that we should not use the actual absolute rainfall measures, because they differ strongly between regions and seasons. This would lead to confounding. In contrast, the deviations between actual and expected rainfall can be considered quasi-random. These deviations are not systematically correlated with maternal and household characteristics, which helps avoid confounding. As detailed in the section "Exposure Measures," we calculate one variable that captures positive deviations and one that captures negative deviations.

We estimate the impact of prenatal rainfall variation on the continuous outcome measure (HAZ) using ordinary least squares (OLS). In all regressions, we adjust for region fixed effects. This means that we only compare growth outcomes of children residing in the same regions but exposed to different rainfall conditions during gestation. Using region fixed effects implies that we automatically adjust for all regional geographic and population characteristics that are constant over time, which further helps taking out potential for confounding.

We furthermore adjust for child age (in months), child sex, maternal age at birth (in years), and rural residence to increase the precision of our estimates. To account for time trends, we include the child's year of birth and its square. Standard errors are clustered at the regional level. For binary outcome measures (stunted/severely stunted), we use logistic regressions using the same set of covariates as described above.

Heterogeneity

To identify particularly vulnerable subgroups, we conduct a heterogeneity analysis estimating associations separately for children by various dimensions of socioeconomic and background characteristics: mothers with no formal education vs at least primary education, by household wealth and by Indigeneity—in the Peruvian context, Indigenous populations tend to rely more strongly on natural ecosystems and have limited access to conventional healthcare.[30] Prior research has shown that education can protect against external hazards by improving health knowledge, access to information, income stability, and decision-making autonomy on health matters.[31-33] Moreover, in the Peruvian context, Huicho et al.[34] found that education played a crucial role in the drastic stunting reduction between 2000 and 2012. Furthermore, we test for differences between rural areas—where people may be more dependent on rainfed agriculture—and urban areas. Additionally, we examine differences by sex.

Finally, we examine heterogeneities by the three main climatic zones in Peru (see Figure 1 for an overview of climatic zones). We conduct stratified analyses for the arid costal area ("Coast"), the highlands ("Andes"), which are characterized by distinct rainy and dry seasons, and the humid tropical rainforest ("Selva") to account for potential heterogeneities due to the general regional climate.[15]

Sensitivity and robustness

We implement additional analyses to test the stability of our results. First, we conduct our main analyses while including mother fixed effects instead of region fixed effects. These analyses solely utilize between-sibling variation, which means that the potential for confounding is considerably reduced. The sample contains 50 986 mothers, leading to an average of 1.27 children per mother. For binary outcomes, these analyses are run as conditional logit regressions. Second, we restrict the sample to children whose mothers have lived in the same residence for at least 6 years. The data do not include children's place of birth, so that this robustness check increases the precision in exposure calculation. Third, we include birth month fixed effects to test the stability of the results when adjusting for seasonality and survey year fixed effects to capture survey-specific characteristics. Fourth, to ensure that the results are not sensitive to the choice of time trend, we replace the birth year based time trend with a survey year time trend. Lastly, we conduct a balancing test by replacing the dependent variable with maternal education, rural residency, Indigeneity, and household wealth. This analysis assesses the core assumption of our quasi-experimental design, i.e., that prenatal rainfall anomalies are not correlated with household and family background characteristics that could otherwise confound the relationship between rainfall anomalies and child growth.

Results

Sample characteristics

Table 1 summarizes key sample characteristics. The main analytical sample includes 64 859 children under the age of five with valid HAZ measurements and complete information on covariates and variables used in heterogeneity analyses. The average HAZ is -1.34, with 28.9% of children classified as stunted and 8.6% as severely stunted, consistent with high stunting rates observed in Peru during this period.[10] DHS households are relatively poor, following a classification based on housing conditions, ownership of goods, and access to water.[35] This classification was only introduced after the first two survey rounds used in this study, resulting in a smaller number of observations for this variable. Based on household language, 25.3% of children are classified as Indigenous, though data are incomplete for the 2000 survey round. Table S1 presents sample characteristics

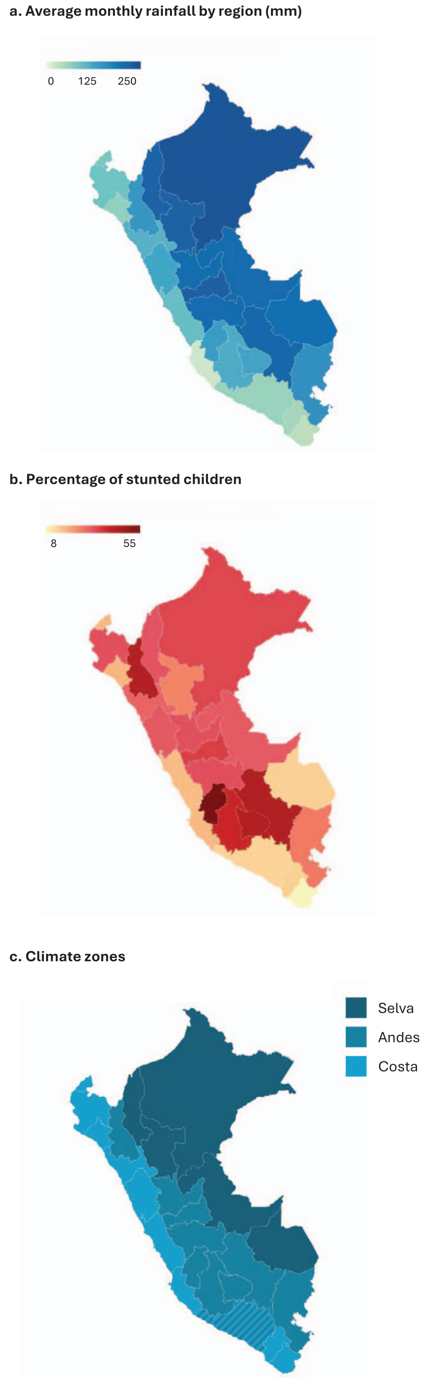

Figure 1 Spatial distribution of monthly rainfall, child stunting, and climate zones in Peru Panel (A) displays average monthly rainfall (in mm) by region (reference period: 1980-2012). Panel (B) presents the regional prevalence of stunting among children under 5 years of age. Panel (C) shows the classification of Peru into three major climate zones: Selva, Andes, and Costa. Costa refers to the arid coastal region of Peru and includes the departments of Tumbes, Piura, Lambayeque, La Libertad, Áncash, Lima, Ica, Arequipa, Moquegua, and Tacna. Andes encompasses the highland areas characterized by distinct rainy and dry seasons. This zone includes Cajamarca, Huánuco, Pasco, Junín, Huancavelica, Ayacucho, Apurímac, Cusco, Puno, and Arequipa. Selva describes the humid rainforest region of Peru and includes Amazonas, Loreto, San Martín, Ucayali, and Madre de Dios. Arequipa is included in both the Costa and Andes zones, as it spans both geographical areas. The department's population is distributed between the coastal lowlands and the highland regions. Source: own illustration.

Table 1 Characteristics of 64 859 children (ages 0-5 years), Peruvian Demographic and Health Surveys, 1996-2012.

Variables	Mean	SD	Observations
Child characteristics			
HAZ	−1.34	1.27	64 859
Stunted (0/1)	0.29	0.45	64 859
Severely stunted (0/1)	0.09	0.28	64 859
Child age (months)	29.89	17.17	64 859
Child female (0/1)	0.50	0.50	64 859
Rainfall variation during pregnancy			
Positive rainfall deviation[a]	0.08	0.28	64 859
Negative rainfall deviation[a]	0.12	0.15	64 859
Maternal and household characteristics			
Maternal age at birth	26.86	6.88	64 859
Rural (0/1)	0.47	0.50	64 859
Maternal education (in years)	7.60	4.38	64 859
Mother at least primary education (0/1)	0.94	0.25	64 859
Poor (first and second wealth quintile) (0/1)	0.58	0.49	38 395
Indigenous (0/1)	0.25	0.44	53 196

Abbreviation: HAZ, height-for-age *z*-score.
Summary statistics are based on the full analytical sample unless otherwise indicated.
[a]Rainfall variables refer to the prenatal period. The variable positive rainfall deviations equals the *z*-score for region-and-time specific rainfall, but is set to zero for negative rainfall deviations. Vice versa for negative rainfall deviations, which is additionally multiplied by minus 1 to obtain positive values.

stratified by the binary exposure measures. Figure 1 displays the climatic, nutritional, and geographic context of the study setting.

Impacts of rainfall variation on height for age

Table 2 displays associations between prenatal rainfall variation and childhood growth outcomes. The coefficients in Panel A represent the change in HAZ and in the odds of stunting associated with a one standard deviation increase in positive rainfall anomalies during pregnancy. The coefficients in Panel B compare child height-for-age and the odds of stunting for children exposed to high and low rainfall anomalies during gestation, as compared to those whose in utero period did not overlap with rainfall anomalies.

Panel B shows that positive rainfall deviations above the 80th percentile are significantly associated with lower HAZ, indicating that exposure to excess rainfall during pregnancy (>80th percentile) is associated with a 0.073 (95% confidence interval [CI], −0.112 to −0.035) decrease in HAZ. Prenatal exposure to positive rainfall deviations above the 80th percentile also increases the odds of being stunted (1.139; 95% CI, 1.064 to 1.220). For the continuous measure for positive rainfall deviations, the coefficients point into the same direction, but cannot statistically be distinguished from chance (Panel A).

Exposure to negative deviations below the 20th percentile is associated with decreased odds of being severely stunted (0.843; 95% CI, 0.772 to 0.919). For the continuous exposure measure, the pattern is similar but exhibits wide CIs.

Differential vulnerabilities

Table 3 displays the results of subgroup analyses. Adverse impacts are larger among children born to mothers without formal education (note that precision is lower in this group due to a smaller sample size). A one-standard deviation increase in positive prenatal rainfall anomalies is associated with 0.407 higher HAZ among children to mothers without formal education (Panel A, [1]). No heterogeneity by poverty appears. The beneficial impacts of rainfall below the 20th percentile on HAZ are larger for children from Indigenous descent, as is the adverse impact of positive rainfall anomalies.

The adverse impacts of more rainfall (continuous measure), and high rainfall deviations are stronger in rural areas. Regarding heterogeneity by sex, there appear to be stronger adverse associations of rainfall above the 80th percentile for girls, while the association between droughts and improved height growth is larger for boys.

Table 4 shows heterogeneities by climatic region. The benefits of reduced rainfall are concentrated in the arid coastal regions. Adverse impacts of high rainfall levels appear in all three regions but only appear for excessive rainfall levels in the arid coastal regions.

Robustness and sensitivity

The mother fixed effects analyses support the conclusions from the main analyses, with results that are similar, but generally larger in effect size (Table S2). The balancing test showed that prenatal rainfall variations are not systematically associated with family and household characteristics (Table S3). Moreover, the results are robust across all further sensitivity checks, i.e., restricting the sample to households that did not move within the last 6 years, adding fixed effects for survey wave and birth month as well as replacing the birth year based time trend with a time trend based on survey year and its square (Table S4).

Discussion

This study contributes to the evidence on how rainfall variability during pregnancy shapes early-life health outcomes in Latin America by documenting disparities in child growth impacts among Peruvian children under 5 years. We show that prenatal exposure to higher rainfall is associated with impaired child growth, while rainfall deficits (though not if very high) in coastal regions are linked to improved outcomes. Adverse impacts are most pronounced among rural, Indigenous children and those born to mothers without formal education. These findings show that rainfall anomalies during pregnancy can affect child health and that impacts vary by socioeconomic

Table 2 Associations between prenatal rainfall variation and HAZ, Stunting and Severe Stunting among children (ages, 0-5 years), with continuous and binary exposure measures, Peruvian Demographic and Health Surveys, 1996-2012.

Panel A: prenatal rainfall anomalies: continuous exposure measures			
	HAZ OLS (1)	Stunted Logit (2)	Severely stunted Logit (3)
Positive prenatal rainfall deviations	−0.099 [−0.265 to 0.066]	1.196 [0.950 to 1.506]	1.122 [0.868 to 1.451]
Negative prenatal rainfall deviations	0.083 [−0.134 to 0.299]	0.849 [0.619 to 1.165]	0.662 [0.436 to 1.004]
Observations	64 859	64 859	64 859
Panel B: prenatal rainfall anomalies: binary exposure measures			
	HAZ OLS (4)	Stunted Logit (5)	Severely stunted Logit (6)
Prenatal rainfall >80th percentile	−0.073 [−0.112 to −0.035]	1.139 [1.064 to 1.220]	1.078 [0.968 to 1.201]
Prenatal rainfall <20th percentile	0.029 [0.002 to 0.056]	0.969 [0.930 to 1.009]	0.843 [0.772 to 0.919]
Observations	64 859	64 859	64 859

Abbreviation: HAZ, height-for-age *z*-score.
Each column in each panel shows the coefficients [with 95% CIs] from a separate regression. Each panel presents the results for a different exposure definition. All models were adjusted for child sex, child age in months, maternal age at birth, a rural dummy, child's birth year, and its square as well as region fixed effects. Robust standard errors were clustered at the regional level.

background and climate zones. Climate shocks thus risk reinforcing social inequities, which contributes to the understanding of the origins of early-life health disparities in Peru.

Our findings on the impacts of excess rainfall on height growth are broadly consistent with earlier work by Le and Nguyen,[5] McMahon and Gray,[21] and Dimitrova and Muttarak.[20] The high prevalence of rain-fed agriculture in Peru implies sensitivity to rainfall variability.[17] By considering both continuous and percentile-based exposure measures, we show that only high excess rainfall (>80th percentile) significantly impairs growth. This may reflect heightened agricultural sensitivity.[8,36,37] Rainfall anomalies can disrupt agricultural cycles, reduce crop yields, and impair household food security.[9] Higher rainfall deviations may more strongly affect maternal nutrition during pregnancy, which is a determinant of fetal and early-life growth.[18,38] The evidence on the impacts of lack of rainfall is mixed. While several studies report adverse impacts on child growth,[16-19,28] others find no such relationship.[5,39] In our sample, we do not detect a consistent pattern of associations between negative rainfall deviations and height growth. Future research is needed to better understand the mechanisms underlying these divergent findings.

The main contribution of this research is that beyond documenting adverse impacts across the full population, for the first time, for Peru, it is shown that vulnerabilities to prenatal rainfall variation vary across climatic zones and socioeconomic background characteristics. While we generally find that excess rainfall impairs growth, rain deficits are associated with improved HAZ in the coastal regions. Peru's climatic dynamics might explain this pattern. For example, during La Niña events, the typically dry coast can benefit from increased Andean rainfall, which enhances irrigation in river valleys descending from the Andes.[40] Rainfall patterns affecting river water levels may indirectly support agricultural productivity in coastal areas, even when local precipitation is low. For example, Chacón-Montalván et al.[41] find that rainfall anomalies are closely associated with river-level changes in the Amazon. Moreover, coastal households can ensure food security with other nutritional sources such as fish.[42] By contrast, adverse impacts of excess rainfall are strongest in the Andes, where multiple stressors such as low oxygen levels, colder temperatures, limited access to health care, and poorer diets increase vulnerability.[43] Given the similarly sharp ecological gradients and climatic variability across many Latin American countries, our findings highlight the need for future research in the region to carefully account for within-country heterogeneity when assessing the health impacts of climate shocks. This study, to the best of our knowledge, is the first to examine heterogeneities by climatic region. Future work should evaluate whether these patterns generalize to other Latin American contexts and beyond.

Moreover, we find that children of mothers without formal education and those in rural households are particularly affected, consistent with climate–health research in other low- and middle-income countries (LMICs).[5,20,21,44] Higher vulnerability in rural areas likely reflects greater dependence on rain-fed agriculture.[8] Although stunting is more prevalent in rural Peru,[43] effect-size differences between rural and urban areas are modest—possibly because many urban households also engage in agriculture.[17] Agriculture remains a key livelihood source, employing nearly one quarter of the national workforce, two-thirds of whom live in rural areas.[45]

While we find adverse impacts on linear growth for both Indigenous and non-Indigenous children, they are more pronounced among Indigenous children. This finding aligns with Nicholas et al.[12] who report stronger growth impairments among rural Indigenous children, though their findings suggest a protective association for Indigenous children in urban areas. By contrast, the consistently large and significant coefficients in our results imply that Indigenous children face heightened vulnerability regardless of their residence. We proxied for Indigeneity by the language spoken at home, which is not available for the survey year 2000 and may not include all Indigenous households, potentially contributing to differences in findings. Future research is necessary to shed more light on underlying

Table 3 Associations between prenatal rainfall variation and HAZ among children (ages 0-5 years) by socioeconomic characteristics, with continuous and binary exposure measures, Peruvian Demographic and Health Surveys, 1996-2012.

	Mother no formal education	**Mother at least primary education**	**Poor household**	**Non-poor household**	**Indigenous**	**Non-indigenous**	**Rural household**	**Urban household**	**Female**	**Male**
Panel A: prenatal rainfall anomalies: continuous exposure measures										
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Positive prenatal rainfall	−0.407 [−0.785 to −0.029]	−0.092 [−0.255 to 0.070]	−0.019 [−0.183 to 0.145]	−0.138 [−0.466 to ,0.191]	−0.519 [−0.931 to −0.107]	−0.226 [−0.433 to −0.019]	−0.185 [−0.360 to −0.009]	−0.067 [−0.200 to 0.066]	−0.115 [−0.284 to 0.055]	−0.085 [−0.248 to 0.078]
Negative prenatal rainfall	−0.084 [−0.595 to 0.427]	0.094 [−0.115 to 0.302]	0.049 [−0.050 to 0.148]	−0.027 [−0.217 to 0.163]	−0.015 [−0.347 to 0.317]	0.058 [−0.131 to 0.248]	0.116 [−0.148 to 0.380]	0.034 [−0.201 to 0.268]	0.041 [−0.251 to 0.334]	0.124 [−0.045 to 0.294]
Panel B: prenatal rainfall anomalies: binary exposure measures										
	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)
Prenatal rainfall >80th percentile	−0.120 [−0.251 to 0.011]	−0.071 [−0.109 to −0.034]	−0.008 [−0.051 to 0.035]	0.014 [−0.032 to 0.060]	−0.086 [−0.144 to −0.028]	−0.062 [−0.104 to −0.020]	−0.106 [−0.165 to −0.047]	−0.046 [−0.079 to −0.012]	−0.100 [−0.144 to −0.056]	−0.046 [−0.096 to 0.004]
Prenatal rainfall <20th percentile	0.066 [−0.022 to 0.155]	0.027 [0.002 to 0.052]	0.007 [−0.018 to 0.032]	0.022 [−0.016 to 0.059]	0.061 [0.012 to 0.110]	0.023 [−0.007 to 0.053]	0.030 [−0.008 to 0.069]	0.029 [−0.008 to 0.066]	0.010 [−0.030 to 0.049]	0.047 [0.013-0.081]
Observations	12 393	12 386	13 152	13 144	12 940	12 934	12 972	12 966	13 402	13 391

Abbreviation: HAZ, height-for-age *z*-score.
This table displays HAZ estimates based on continuous (Panel A) and percentile-based (Panel B) rainfall deviations for samples stratified by socioeconomic characteristics. Each column in each panel shows the coefficients from a separate OLS regression [with 95% CIs]. Household poverty is defined on wealth quintiles (first and second wealth quintile)—see “Sample characteristics” for details. Indigeneity is classified based on language spoken in the household. All models were adjusted for child sex, child age in months, maternal age at birth, a rural dummy, child’s birth year and its square as well as region fixed effects. Robust standard errors were clustered at the regional level.

Table 4 Associations between prenatal rainfall variation and HAZ among children (ages 0-5 years) by climate region of residence, with continuous and binary exposure measures, Peruvian Demographic and Health Surveys, 1996-2012.

Panel A: prenatal rainfall anomalies: continuous exposure measures			
	Costa	**Andes**	**Selva**
	(1)	(2)	(3)
Positive prenatal rainfall	−0.019	−0.773	−0.398
	[−0.114 to 0.076]	[−0.975 to −0.570]	[−0.726 to −0.071]
Negative prenatal rainfall	0.215	−0.116	−0.149
	[0.005 to 0.424]	[−0.510 to 0.277]	[−0.511 to 0.213]
Observations	27 060	25 585	14 122
Panel B: prenatal rainfall anomalies: binary exposure measures			
	Costa	**Andes**	**Selva**
	(4)	(5)	(6)
Rainfall >80th percentile	−0.076	−0.075	−0.052
	[−0.151 to −0.001]	[−0.115 to −0.036]	[−0.146 to 0.042]
Rainfall <20th percentile	0.025	0.050	-0.001
	[−0.003 to 0.052]	[−0.005 to 0.106]	[−0.067 to 0.065]
Observations	27 060	25 585	14 122

Abbreviation: HAZ, height-for-age *z*-score.
This table displays HAZ estimates based on continuous and percentile-based rainfall deviations for each climate region separately. Each column in each panel shows the coefficients from a separate OLS regression [with 95% CIs]. Each panel presents the results for a different exposure definition. All models were adjusted for child sex, child age in months, maternal age at birth, a rural dummy, child's birth year and its square as well as region fixed effects. Robust standard errors were clustered at the regional level.

mechanisms. Indigenous populations are often overlooked in climate-health research, despite being among the most vulnerable due to their reliance on natural ecosystems, pre-existing health disparities, and limited healthcare access.[46,47] Already today, the Indigenous population in the Amazonian Basin in Peru are experiencing the largest climatic changes with increasing temperatures and increasing risk of drought.[30]

We did not find heterogeneities by child sex, hence this study does not support the Fragile Male Fetus Hypothesis, which posits greater susceptibility of male fetuses to stressors during gestation.[48] This finding is consistent with previous studies.[49,50] Fitz and League[51] even find stronger impacts among girls in Brazil. Although stunting prevalence is generally higher among girls in Latin America,[52] this pattern has not been clearly linked to gender-based disparities in household nutrition allocation, indicating that gendered vulnerabilities may be context-specific. Similarly, although low socioeconomic status and poverty are widely recognized as vulnerabilities,[14,53] our analysis did not reveal differences between poor and non-poor households. However, wealth information was only available for a subset of the sample, which could lead to bias in this result. Moreover, the DHS wealth index has been criticized for being too focused on urban living conditions, which may make it less accurate for measuring poverty in rural areas.[54] These factors make it difficult to draw clear conclusions about wealth's role in the relationship between prenatal rainfall anomalies and child growth.

The key strength of this study lies in leveraging exogenous rainfall variation in a large dataset and combining it with stratified analyses by socioeconomic background and climatic region, providing novel evidence on disparities in climate impacts on child health in Peru. Nonetheless, several limitations remain. The absence of GPS coordinates restricts geographic precision to the regional level, masking within-region rainfall variation in large or climatically diverse areas such as Loreto and Arequipa. Moreover, ERA5 reanalysis data may also diverge from observational datasets, particularly in the Amazon basin where it has overstated drying trends.[55] However, since our analysis relies on within-region variation, this limitation is unlikely to substantially confound our results. Furthermore, since gestational duration is not observed, we assume full-term pregnancies. To the extent that pregnancies are longer or shorter, this may introduce nonsystematic measurement error in our exposure variable, which would attenuate estimates toward zero.

Future research could place greater emphasis on country-specific dynamics and the multiple pathways through which rainfall anomalies affect child health. Advancing this research agenda will require more comprehensive data, including household GPS coordinates and longitudinal health tracking. Interdisciplinary work should also rely on standardized and systematized data collection practices that enable comparability across contexts.[56] Finally, improving the monitoring and quantification of climate-related health impacts is essential to design context-sensitive adaptation strategies in Latin America and beyond.[57]

In conclusion, this study underlines that rainfall anomalies contribute to social inequities in child health. To counter this, it is important to understand which policy measures can reduce vulnerability to rainfall-related health risks in early life in Latin America and beyond. For example, evidence from Peru suggests that Conditional Cash Transfer programs such as JUNTOS can improve child growth and buffer negative impacts of other shocks.[17,58] Moreover, it has been shown that strengthening maternal education can help build resilience to rainfall-related health risks.[21,46,59] Our findings, showing that depending on context, both positive and negative rainfall anomalies can affect child health, imply that further research is needed to better inform policy design.

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Author contributions

L.H. participated in the conceptualization (equal), data curation (lead), formal analysis (lead), investigation (lead), methodology (equal), project administration (supporting), writing—original draft (lead), writing—review & editing (equal). R.vE. participated in the conceptualization [supporting], formal analysis (supporting), funding acquisition [lead], investigation [supporting], methodology (equal), resources (lead), supervision (supporting), validation (equal), writing—review & editing (equal). F.P. participated in the conceptualization (equal), data curation (supporting), formal analysis (supporting), funding acquisition (supporting), investigation (supporting), methodology (equal), project administration (lead), supervision (lead), writing—original draft (supporting), writing—review & editing (equal)

Supplementary material

Supplementary material is available at *AJE Advances: Research in Epidemiology* online.

Conflicts of interest

None declared.

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Data availability

The data underlying this article are from the Demographic and Health Surveys (DHS) Program. Due to data use agreements, we are unable to share the data directly. However, the DHS data are publicly available upon application to the DHS Program (http://dhsprogram.com/).

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