



# After the floods: Differential impacts of rainfall anomalies on child stunting in India



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## 1. Introduction

The frequency and magnitude of floods is projected to increase in the next decades due to global warming, affecting up to 1.2% of the global population by the end of the century (Hirabayashi et al., 2013). With an increase in extreme precipitation events due to climate change, India has become more prone to floods (Ali et al., 2019). This has resulted in serious damage, with the recent flooding in Kerala during the 2018 monsoon season affecting the livelihoods of 23 million people and causing losses amounting to \$2.9 billion US dollars (EM-DAT, 2019).

Apart from economic loss and damage, floods also have adverse impacts on human health. Contaminated floodwater may lead to outbreaks of infectious diseases, such as diarrhoea, leptospirosis and cholera (Ahern et al., 2005; Alderman et al., 2012). Increase in vector-borne illnesses is also observed after floods due to the accumulation of stagnant water, which is a breeding ground for mosquitos and other disease vectors. In low- and middle-income countries, where infectious diseases remain one of the leading causes of death, floods can pose a serious threat to public health.

Floods and heavy precipitation can also damage crops, disrupt food supplies and economic livelihoods (Watts et al., 2018), thus affecting human health indirectly as well. In the long-term, floods have been linked to elevated risk of non-communicable diseases, psychosocial distress, and poor birth outcomes (Alderman et al., 2012; Zhong et al., 2018).

The health burden on children can be particularly severe in the event of floods and related disasters. Reduced food intake and the presence of infectious diseases in young children can lead to undernutrition and stunted growth (de Onis, 2007). Being severely stunted as a child, in turn, is associated with lower school performance, reduced life-time earnings, and a predisposition to chronic diseases, among other disadvantages during adolescence and adulthood (Adair et al., 2013; Alderman, 2006; Black et al., 2008). Natural disasters, including floods, can therefore considerably aggravate children's health and economic prospects, particularly in low-, and middle-income countries, which have higher level of vulnerability to such disasters and lower level of preparedness.

Nevertheless, the impacts of floods and extreme precipitation on child health are not well understood (Phalkey et al., 2015). A few studies report an increased risk of undernutrition in India (Muttarak and Dimitrova, 2019; Rodriguez-Llanes et al., 2016, 2011), Nepal (Gaire et al., 2016) and Bangladesh (del Ninno and Lundberg, 2005), while others do not find lasting effects of floods on child health in the South Asia region (Joshi et al., 2011; Stewart et al., 1990). The existing evidence is mostly based on small-scale surveys and/or constrained to specific geographic areas, which presents a major limitation in the literature. Rodriguez-Llanes et al. (2016, 2011), for example, use data for 14 flooded and 18 non-flooded villages in rural eastern India, while Muttarak and Dimitrova (2019) focus on extreme rainfall events in southern India. Furthermore, focusing on identifying average effect sizes, the majority of existing studies fail to consider the seasonality of flood risks in South Asia, and, pay no attention to differential levels of vulnerability across population subgroups.

In view of the above, this study provides three novel contributions to the literature. First, we combine data from a nationally representative household survey for India and geo-referenced climate data to assess the impacts of rainfall anomalies on child undernutrition on a larger scale than previous studies. We focus on children under the age of five ( $n = 220,823$ ) and use a measure of stunting, which reflects long-term exposure to low food intake and diseases (WHO, 2010). Additionally, we focus on rainfall anomalies during the monsoon season, when the risk of floods in India is the highest (Ali et al., 2019).

As a second contribution, we apply the demographic differential vulnerability approach to identify specific population subgroups that should be targeted for policy intervention (Muttarak et al., 2016) We explicitly consider how factors at the individual and household level such as child's gender, urban–rural residence, mother's level of education, and family's caste and wealth status modify the degree of susceptibility to childhood undernutrition. All of these factors are important predictors of a child health status (Kanjilal et al., 2010; Pathak and Singh, 2011; Subramanyam et al., 2010) and can reveal critical disadvantages in coping with the effects of climate shocks (Brouwer et al., 2007; Friel et al., 2008).

In particular, the effect of mother's education on child

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undernutrition is comprehensively investigated. Previous research has established that a higher level of education among mothers correlates with better health outcomes for their children (Alderman and Headey, 2017; Fuchs et al., 2010). In this study, we explore the protective effect of mother’s education in comparison to household wealth and we empirically unpack the mechanisms through which mother’s education influences child nutritional outcomes (Abuya et al., 2012). This knowledge has proved useful not only in identifying which population subgroups to target for policy intervention during extreme climate events but also which measures can be most effective.

The third analytical contribution to the literature concerns the potential role of water, sanitation and hygiene (WASH) interventions in reducing children’s health risks associated with extreme rainfall events. There is strong evidence that inadequate WASH conditions hinder early child development (Ngure et al., 2014). In India, access to sanitation facilities and clean water is still limited, and poor hygiene practices, such as open defecation, are common (UNICEF et al., 2019). Considering that heavy rains can lead to water contamination and outbreaks of bacterial infections, it is important to investigate how much of the health burden on children can be alleviated through improved water, sanitation and hygiene.

This study focuses on stunting as a measure of child undernutrition, which is typically caused by infections and inadequate nutrition during a child’s early years of life (WHO, 2010). Stunting can be interpreted as the failure to reach a child’s full growth potential. On a societal level, high stunting prevalence is indicative of poor socioeconomic conditions (Bommer et al., 2019). Severe stunting can impair not only the physical but also the mental and cognitive development of a child, causing lifetime disadvantages. Children who are severely stunted have been found to perform worse in school, have reduced intellectual capacity, and lower lifetime earnings (Adair et al., 2013; Alderman, 2006; Black et al., 2008; Victora et al., 2008). Likewise, women who were stunted in childhood are more likely to experience complications during labour and give birth to stunted children, which creates a ‘vicious cycle’ of malnutrition (Wells, 2017; WHO, 2010). If climatic shocks do exacerbate stunting, targeted nutrition interventions should be provided to reduce the short- and long-term adverse impacts on children.

This line of research is particularly relevant for India where as many as 34.7% of children aged under five are stunted (UNICEF et al., 2018). In spite of some progress to tackle malnutrition having been made in the past decade, India remains among the countries with the highest levels of childhood undernutrition in the world, being home to almost a third (31%) of all stunted children (Development Initiatives, 2018). This represents an enormous loss of human potential, given the long-term effects of stunting on health, human capital and productivity. Further progress could be slowed down or even reversed due to climate change. Climate projections show that the risk of extreme rainfall

events will increase over South Asia in the coming decades (Hijioka et al., 2014; Hirabayashi et al., 2013). The Intergovernmental Panel on Climate Change (IPCC) Special Report on 1.5 °C in fact has warned that with increasing risks from heavy precipitation events, including flooding and tropical cyclone over the North Indian ocean, food production in agricultural economies like India will decline (IPCC, 2018). It is not yet clear how these trends will affect children’s health and wellbeing in the region. Improving the knowledge in this field thus would be crucial for designing early response mechanisms and targeted intervention programs.

The remainder of the paper is organised as follows. In Section 2, we present the conceptual framework describing determinants of child undernutrition in the context of climate change, with a focus on the demographic differential vulnerability approach. The data and empirical strategy are described in Section 3 and Section 4, respectively. The results are presented in Section 5 and a discussion of the findings and conclusion are offered in Section 6.

## 2. Conceptual framework

Back in 1990, the UNICEF developed a conceptual framework to explain the underlying causes of child undernutrition (UNICEF, 2014). In particular, the framework identifies immediate, underlying and basic causes, and describes how these are interconnected. At the immediate level, food and nutrient intake and exposure to diseases are included. These factors are influenced by the underlying social and economic resources available to households, which determine food availability, health care use, feeding practices, water, sanitation and hygiene. Basic causes involve societal structures and processes, such as the economic system, societal norms, institutions and governance, which can lead to unequal distribution of capital. This multi-dimensional framework allows national and local organizations to pinpoint areas where the most effective interventions can be made to improve child nutrition. Whilst in the early 1990s, climatic factors were not originally included in the UNICEF conceptual framework of undernutrition, it later became clear that extreme climate events and climate variability are a key source of shocks that can disrupt resources and livelihoods.

Tirado et al., 2013 (p. 536) describe the various pathways through which climate extremes, variability and change influence child undernutrition. One important channel is through the underlying causes of undernutrition, such as food access, maternal and child care, feeding practices, access to health services and household environmental health (sanitation, hygiene and safe drinking water). Climatic factors can also influence the basic causes of undernutrition, for example by provoking conflicts and thus impacting household socioeconomic resources indirectly (Smith, 2014).

Fig. 1 displays a conceptual framework linking the various factors

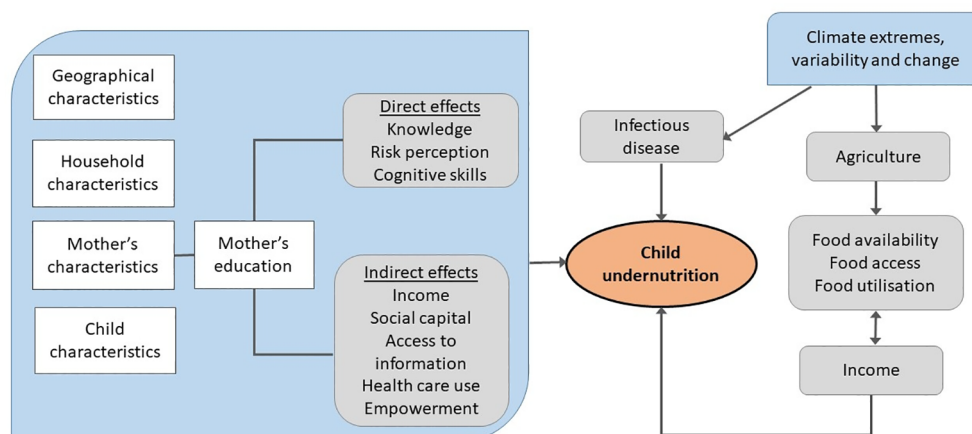


Fig. 1. Conceptual link between climatic factors, individual, household and geographical characteristics and child undernutrition.

that contribute to child undernutrition. Irrespective of climate conditions, nutritional status is determined by *who* a child is (e.g. age, sex, birth order), *who* a caregiver is (e.g. mother's education, mother's age), *what* type of household the child lives in (e.g. wealth, economic activity, home environment), and *where* the household is located (e.g. rural/urban residence). In terms of child characteristics, boys are generally more likely to be undernourished than girls (Harding et al., 2018). This is partly due to behavioral and biological differences, such as higher calorie needs of boys (Wamani et al., 2007). Birth order also seems to be a risk factor, particularly in African countries (Howell et al., 2016). Differential parental investment and allocation of household resources may partially explain the above patterns. Indeed, childcare practices, including infant feeding, food preparation and health-seeking behaviour, are highlighted in the UNICEF framework as key factors explaining nutritional outcomes.

Since mothers are typically the main caregivers of young children, maternal characteristics matter substantially for child growth and development. In particular, mother's education is central in shaping child health and nutritional outcomes, which are fundamental to child survival (Alderman and Headey, 2017; Arthur et al., 2015; Fuchs et al., 2010). Likewise, household socioeconomic resources also influence undernutrition though access to food and health care, while access to safe water, sanitation and hygiene (WASH) is key for preventing infectious diseases leading to growth faltering (Cumming and Cairncross, 2016; Humphrey et al., 2019). Geographical location, such as rural/urban residence, is also highly important since it can determine the overall standard of living, access to health services and infrastructure (Fox and Heaton, 2012). The above-mentioned individual, household and geographical characteristics can therefore moderate the impact of climatic shocks on child health.

Fig. 1 further shows that climate variability and extreme climate events, such as floods and droughts, disrupt agricultural production and consequently household food security. Household food insecurity can harm child growth and development, especially for children under five – the age when nutrients are vital for the development of key brain processes and structures as well as physical growth. The impact of climatic shocks on child undernutrition, however, is not distributed evenly across population subgroups. The degree to which a child is affected by climate shocks is determined by the ability of the household to respond to such shocks. Wealthier households, for instance, generally have better coping capacities during climatic shocks because they are able to draw upon their savings or have better credits to borrow (Narayanan and Patnaik, 2010; Patnaik et al., 2016). Being able to smooth consumption, these households therefore have capacity to protect their children against undernutrition. On the other hand, households with a female head have lower capacity to cope with shocks due to both the economic disadvantage associated with a female gender and a childcare burden from being a one adult person in a household (Flatø et al., 2017).

The emphasis on the unequal distribution of the impact of climatic shocks is in line with the demographic differential vulnerability approach (Muttarak et al., 2016). Apart from age, gender and income, recent research has shown that education is one key characteristic explaining differences in vulnerability and adaptive capacity to climate-related disasters (Butz et al., 2014; Muttarak and Lutz, 2014). Studies have shown that education provides a protective effect when it comes to risk perception, disaster preparedness and response to natural disasters (Hoffmann and Muttarak, 2017; Muttarak and Lutz, 2014; Muttarak and Pothisiri, 2013). As a result, households, communities and countries that are highly educated experience lower damages and loss of life due to extreme climate events (KC, 2013; Lutz et al., 2014; Striessnig et al., 2013). Previous research has also shown that mother's education has a protective effect against undernutrition and child mortality (Alderman and Headey, 2017; De Neve and Subramanian, 2018; Pamuk et al., 2011), it is therefore reasonable to assume that during climatic shocks, highly educated mothers are able to draw upon

their social and economic resources to protect the health of their children.

Although the importance of mother's education on child health and wellbeing is widely recognised, the mechanisms are not necessarily well understood (Abuya et al., 2012). Following the frameworks presented by Muttarak and Lutz (2014) and Hoffmann and Muttarak (2017), it can be conceptualised that education translates into better health outcomes for children through direct and indirect channels. Directly, numerical, problem solving and cognitive skills acquired through schooling are skills that are useful for assessing risk and decision making (Bruine de Bruin et al., 2007; Peters et al., 2006). Education also enhances the acquisition of knowledge, including about different aspects of health such as nutrition, disease prevention and treatment<sup>1</sup> (Glewwe, 1999; Heaton et al., 2005; Jalan and Ravallion, 2003; Kovsted et al., 2002).

Mother's education influences child nutritional outcomes indirectly as well, through mediators such as income, social capital, access to information, health care utilisation and female empowerment. These social and economic resources are useful in time of emergency. Indeed, educated people have access to more sources and types of information which can help them make better informed decisions (Neuenschwander et al., 2012; Wen et al., 2011). Better educated women are also more likely to utilise health services during pregnancy and after childbirth (Greenaway et al., 2012; Heaton et al., 2005), whereas less educated women may resort to more "traditional" remedies and seek advice from non-professional health workers.

Female empowerment may be yet another way through which mother's education improves child health. Women's education is associated with greater autonomy in decision-making, higher spending on health-care and freedom of movement (Becker et al., 2006; Bloom et al., 2001). Some evidence suggests that higher decision-making power among women is beneficial for child nutrition (Carlson et al., 2015; Cunningham et al., 2015). This is particularly relevant in low-income contexts, where women are more likely to channel resources towards child welfare than men (McKenna et al., 2019).

Based on the above conceptual framework, we empirically investigate the impact of climate variability on child undernutrition. We pay particular attention to differential vulnerability and explore the mechanisms through which mother's education influences child nutritional outcomes.

### 3. Data and methods

We combine two data sources to assess the impact of rainfall anomalies on child stunting in India: (1) health data from a nationally representative survey and (2) gridded climate data. The two datasets are combined using geo-referenced information of household clusters collected in the survey.

#### 3.1. Health data

We use cross-sectional data from the most recent round of the Demographic and Health Surveys (DHS) for India, collected in 2015–16. The DHS focuses on fertility, health and overall welfare of women in reproductive age and their children. The sample is representative at the national and sub-national level. The child's record is combined with the mother's and household's records to gain information on background characteristics which might be relevant for explaining health disparities in our sample.

<sup>1</sup> The role of literacy as one important aspect of schooling has gained attention in recent research linking female education to maternal and child health outcomes (LeVine et al., 2012). Such research has emphasised that literacy enables women to access and interpret information from popular media and other sources which may benefit her and her children's health.

We focus our analysis on children under the age of five and use anthropometric data to assess their nutritional status. The original sample size is 256,134 children, of which 201 are excluded due to missing information on their geo-location, and additional 35,110 are excluded due missing information on their anthropometric status or other variables used in the regression analysis (see Section 4). The final sample consists of 220,823 children.

Based on standard practice, we calculate height-for-age z-scores (HAZ) relative to the international reference population median (de Onis, 2007). Fig. A1 shows the distribution of HAZ scores in our sample population after excluding biologically implausible scores ( $HAZ > 6$  and  $HAZ < -6$ ). Although the HAZ scores are normally distributed, it is clear that the majority of children aged under five in India have HAZ scores lower than WHO Growth Standards median (0).

Indicators for stunting and severe stunting are then constructed based on the HAZ scores. Children are classified as stunted if their height-for-age is more than two standard deviations (SD) below the WHO Child Growth Standards median and severely stunted if their height-for-age is more than three SDs below the respective WHO median (WHO, 2014). Overall, 38% of children in our sample are stunted and 17% severely stunted.

### 3.2. Climate data

Gridded rainfall data is retrieved from the Climatic Research Unit (CRU) at the University of East Anglia, time-series 3.25, which is available for the whole globe at 0.5° spatial resolution and covers the period from 1901 to 2016 (Harris et al., 2014). The data come from monthly observations at meteorological stations across the world’s land areas. The GPS coordinates of household clusters, provided in more recent DHS rounds, is used to match the location of children with the gridded rainfall data. To keep the identity of survey participants confidential, the DHS displaces household clusters in a random direction by 2 km for urban areas, 5 km for rural areas, and additional 10 km for 5% of all clusters (Burgert et al., 2013). We account for this shift by creating a 10 km radius around each cluster and averaging the climate information for all grid cells that fall within the buffer areas.

We additionally restrict the climate data to the South Asian monsoon season, which spans from June to September. Most rainfall in India is received during this period (see Fig. 2, Panel A) and it is particularly important for agricultural production and other economic activities throughout the year. Heavy monsoon rainfall, however, can lead to flash floods, damaging crops and infrastructure. Delayed and

deficient rainfall, on the other hand, can cause prolonged droughts and deplete fresh-water reservoirs. As seen in Fig. 2, the yearly variations in monsoon season rainfall in India can be substantial.

Apart from the monthly variation, rainfall in India varies greatly by geographic location. Fig. 2 shows the distribution of monsoon season rainfall by grid cell in India between 2010 and 2016, which is the period of our analysis. The different climate regimes can be clearly seen on the map – the arid and semi-arid zones in the north-west and central-south received on average less than 500 mm of monsoon rainfall per year, while the tropical and sub-tropical zones in the north-east and south-west receive over 2000 mm.

We calculate the total amount of monsoon season rainfall in millimeters (mm) for each buffered location. Then we construct a measure of rainfall anomalies as deviations in monsoon season rainfall from the location specific long-term (LT) mean. The long-term is the period from 1970 to 2016. The following formula is applied:

$$anomaly_{j,t} = \frac{level_{j,t} - mean_j^{LT}}{SD_j^{LT}}$$

where  $level_{j,t}$  stands for the level of monsoon season rainfall in cluster location  $j$  at period  $t$ , and  $mean_j^{LT}$  and  $SD_j^{LT}$  are the long-term mean and standard deviation for the same location. Positive anomalies indicate excessive rainfall and negative anomalies indicate deficient rainfall. On average, positive rainfall anomalies are observed in most parts of the country during the 2010–2016 period, except for 2014 and 2015, which were drier than usual (see Fig. A2 in Appendix A).

## 4. Estimation strategy

### 4.1. Baseline model

We use multivariate regression models to explore the association between rainfall anomalies and child nutrition status. An ordinary least squares (OLS) regression model is used for HAZ score and a logistic regression model for the risk of being stunted and severely stunted. Sampling weights, which are part of the complex DHS survey design, are applied in all models.

We additionally control for relevant individual, maternal and household characteristics which may impact child nutrition status. Individual characteristics include child’s sex, whether the child was born a twin, and birth order; maternal characteristics include age at giving birth and level of education; and household characteristics

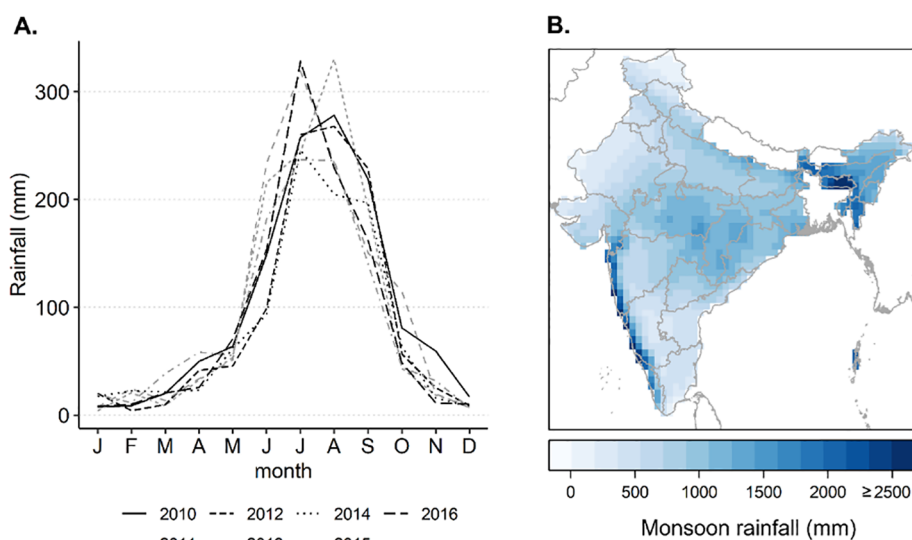


Fig. 2. Monthly rainfall (A), and monsoon season rainfall at 0.5° spatial resolution (B) for 2010–2016, India. Own estimates based on CRU TS 3.25.

**Table 1**  
Summary statistics for main variables of interest.

Variable	Unit	Mean (Proportion)	Std. Dev.
<b>Outcome variables</b>			
HAZ	z-score	-1.43	1.78
Stunted	0/1	0.38	0.49
Severely stunted	0/1	0.17	0.37
<b>Climate variable</b>			
Average rainfall anomalies	z-score	-0.02	0.61
<b>Individual characteristics</b>			
<b>Sex</b>			
Female	0/1	0.48	0.50
male	0/1	0.52	0.50
<b>Twin</b>			
No	0/1	0.99	0.12
yes	0/1	0.01	0.12
Birth order	number	2.27	1.47
<b>Maternal characteristics</b>			
Age at giving birth	years	25.13	4.94
<b>Education</b>			
no	0/1	0.31	0.46
primary	0/1	0.15	0.35
secondary	0/1	0.45	0.50
higher	0/1	0.09	0.29
<b>Household characteristics</b>			
<b>Wealth</b>			
poorest	0/1	0.26	0.44
poorer	0/1	0.23	0.42
middle	0/1	0.20	0.40
richer	0/1	0.17	0.37
richest	0/1	0.14	0.34
Number of under 5 children	number	1.76	0.93
<b>Household head</b>			
male	0/1	0.88	0.33
female	0/1	0.12	0.33
<b>Caste</b>			
other	0/1	0.19	0.39
SC & ST	0/1	0.40	0.49
OBD	0/1	0.41	0.49
<b>Residence</b>			
urban	0/1	0.24	0.43
rural	0/1	0.76	0.43
<b>WASH variables</b>			
<b>Water</b>			
not on premise	0/1	0.38	0.49
on premise	0/1	0.62	0.49
<b>Sanitation</b>			
unimproved	0/1	0.59	0.49
improved	0/1	0.41	0.49
<b>Hygiene</b>			
low	0/1	0.67	0.47
high	0/1	0.33	0.47

include wealth quintile, number of children under the age of five, gender of the household head, caste and urban–rural residence (see Table 1 for detailed summary statistics).

District fixed effects are included to account for location-specific, time-invariant factors. We additionally include fixed effects for the year of interview (2015 and 2016), month of interview, and month of birth to account for time-trending factors. Since children's growth trajectories are not linear, especially during the first months of age, we include restricted cubic age spline with knots at 1, 6, 12, 18, 24, 36 and 48 months of age.

#### 4.2. Differential vulnerabilities

Potential differential vulnerabilities across population subgroups are further examined by the inclusion of an interaction term between the climate measure and specific sociodemographic characteristics of interest. This extended analysis is performed using stunting as an outcome variable. The sociodemographic variables included in the analysis are child's gender, caste, urban–rural residence, household's wealth

status, and mother's level of education<sup>2</sup>.

In the DHS data, caste is classified as “scheduled caste”, “scheduled tribe”, “other backward classes” and “other”. The first two categories refer to the most disadvantaged social classes in India and are grouped together in the subsequent analysis. “Other backward classes” include individuals who also suffer from social and economic disadvantages but to a lesser extent than the scheduled groups. “Other” includes all other social groups and individuals who do not belong to the caste system.

Wealth quintiles are constructed based on the standard DHS procedures using detailed information on household assets and building characteristics (Rutstein and Johnson, 2004). Mother's level of education refers to the highest achieved educational level (no, primary, secondary or higher). In order to capture the interaction effect between mother's education and household wealth, we additionally group the two variables into a single four-level variable: (1) low education and poor, (2) high education and poor, (3) low education and rich, and (4) high education and rich. Mother's education is classified as “low” if she has achieved at most primary education, and “high” if she has achieved at least a secondary level of education. The household is classified as “poor” if it is in the lower two wealth quintiles and “rich” if it is in the upper three wealth quintiles. The above grouping also allows for assessing the relative importance of education as compared to wealth in determining the nutritional outcomes of children, which has previously been applied in the context of infant mortality (Fuchs et al., 2010).

Additionally, available DHS data is used to construct water, sanitation and hygiene indicators, which are then interacted with the climate variable. Water conditions are assessed through the availability of drinking-water source on the premise. Sanitation facilities are classified as either “improved” or “unimproved” based on WHO/UNICEF guidelines (WHO and UNICEF, 2018). “Improved” facilities include flush toilet, piped sewer system, septic tanks and other safe facilities which do not contaminate the living environment. “Unimproved” facilities include pit latrine, bucket toilet, other unsafe facilities or the general lack of sanitation facilities on the premise. Finally, hygiene is assessed through the disposal of child's stool by the mother, which is an important aspect of sanitary behavior. To be considered safe for the household environment, a child's stool needs to be either disposed of in a toilet/latrine or buried, in which case hygiene is classified as “high”. If the child's stool is disposed of in a ditch/garbage, left in the open or in some other way, hygiene is classified as “low” as it can lead to contamination of the living environment. Summary statistics for each WASH variable are provided in Table 1.

#### 4.3. Mediating factors

We additionally perform a mediation analysis to test the importance of different mediators in explaining the association between mother's education and the risk of child stunting. For this purpose, we employ the KHB method (Karlson et al., 2012) which allows for a comparison to be made between the coefficients of nested nonlinear probability models. The KHB method is a type of a decomposition analysis that breaks down the total effect of one variable into direct and indirect effects. This is done by including a set of mediating variables to the baseline model described above, which are expected to (1) impact child stunting and (2) explain some of the effect of mother's education on child stunting.

Potential mediators are grouped into three broad categories: (i) health-specific knowledge, (ii) health-care utilisation and (iii) female empowerment, based on previous literature (see Section 2). The DHS

<sup>2</sup> Looking into differences by partner's level of education would be of interest as well, however, this information was only collected for a small sub-sample of individuals, so we exclude it from the analysis. Furthermore, mother's education is found to have stronger influence on child health than the education of other household members (Karki Nepal, 2018; Lundborg et al., 2014).

questionnaire was thoroughly screened to identify potential mediators in each category. All the questions used to construct the mediator variables were answered by the mother. The following items were selected as proxies of **health knowledge**: general knowledge about HIV, use of mosquito net while sleeping, and disposal of child's stool. In the area of **health-care utilisation**, we selected the following three items: made any antenatal care visits during the latest pregnancy, gave birth in a health facility under the supervision of a trained professional (doctor, nurse or midwife), and completed child vaccination. To assess **female empowerment**, we used information about women's role in taking decisions concerning issues such as healthcare, household purchases and visits to friends and relatives, and their attitude towards wife beating; women who did not participate in decision-making and/or justified wife beating in any situation were considered as not empowered and vice versa. Some of the questions regarding health knowledge and female empowerment were answered in a separate module by a smaller sub-sample of women, which substantially reduced our sample size ( $n = 29,674$ ). See Table C1 in Appendix C for details on all mediator variables used in the analysis<sup>3</sup>. It should be noted that the mediation analysis was restricted by the variables available in DHS and might not fully reflect other possible pathways through which mother's education impacts children's health.

## 5. Results

### 5.1. Baseline model

We find that accumulative exposure to rainfall anomalies from the in-utero period until the time of the survey has a negative and statistically significant association with children's HAZ score (Table 2). For every standard deviation increase in rainfall anomalies, children's HAZ score is reduced by 0.1 point. This means that children who have experienced heavier monsoon season rainfall than usual are more likely to be too short for their age. The results remain robust when we include a list of control variables in the model (Table 2, col. 2), which implies that the relationship between rainfall anomalies and stunting is not driven by sociodemographic factors. This is expected since climatic shocks are largely exogenous events.

The results of the logistic regression model further show that an increase in monsoon season rainfall between the in-utero period and the time of the survey by 1 SD increases the odds of stunting and severe stunting by 16% and 20%, respectively (both > 99% confidence; Table 3, col. 1 and 3). These effects are not trivial: being born to a socially disadvantaged caste (scheduled caste and tribe or other backward class), for example, increases the risk of stunting and severe stunting by a similar magnitude (Table 3, col. 2 and 4).

Most of the sociodemographic variables included in the analysis show significant relationships with HAZ, as well as the probability of stunting and severe stunting. On average, boys have lower HAZ scores (Table 2, col. 2) and are more likely to be stunted and severely stunted than girls (Table 3, col. 2 and 4). We also find that children born to educated women tend to have higher HAZ scores and are less likely to be stunted and severely stunted compared to those whose mothers have no formal education. As expected, children born in wealthier households have, on average, higher HAZ scores and are less likely to be stunted than children born to poorer households. Similarly, children born in a scheduled caste, scheduled tribe or other backward class are more likely to be too short for their age compared to children born in other, not socially disadvantaged, classes.

<sup>3</sup>To ensure that the reduced sample size is not subject to a selection bias, we compared the variable summary statistics between the full and reduced samples (Table C2 in Appendix C). No substantial differences are observed between the two samples. We also verified with the DHS procedures that the sub-sample is randomly selected.

**Table 2**  
Impacts of rainfall anomalies on HAZ score, children aged 0–5.

	HAZ (OLS coef.)	(0.02)	HAZ (OLS coef.)	(0.02)
Average rainfall anomalies	−0.10***	(0.02)	−0.11***	(0.02)
<b>Individual characteristics</b>				
Sex (ref. = female)				
male			−0.07***	(0.01)
Twin (ref. = no)				
yes			−0.39***	(0.06)
Birth order			−0.06***	(0.01)
<b>Maternal characteristics</b>				
Age at giving birth			0.02***	(0.002)
Education (ref. = no)				
primary			0.07***	(0.02)
secondary			0.19***	(0.02)
higher			0.37***	(0.02)
<b>Household characteristics</b>				
Wealth (ref. = poorest)				
poorer			0.14***	(0.02)
middle			0.28***	(0.02)
richer			0.43***	(0.02)
richest			0.66***	(0.03)
Number of under 5 children			−0.04***	(0.01)
Household head (ref. = male)				
female			−0.01	(0.02)
Caste (ref. = other)				
scheduled caste and tribe			−0.19***	(0.02)
other backward class			−0.09***	(0.02)
Residence (ref. = urban)				
rural			0.05*	(0.02)
Observations	220,823		220,823	
R <sup>2</sup>	0.11		0.14	

Notes: \* $p < 0.05$ , \*\* $p < 0.01$ , \*\*\* $p < 0.001$ . Average rainfall anomalies are measured from the in-utero period up until the time of the interview. Age splines and fixed effects for month of birth, month of interview, year of interview and district are included but not displayed. Robust standard errors are reported in parenthesis. Standard errors are clustered at the district level. Sampling weights are applied.

We perform a series of robustness checks to rule out potential biases in our model specification and sample composition. First, to test for a non-linear association between monsoon season rainfall and the undernutrition indicators, we include the quadratic polynomial of the rainfall anomalies measure. This would allow us to detect a potential U-shaped relationship between rainfall anomalies and child undernutrition, i.e. undernutrition increasing both with dry and wet monsoon weather<sup>4</sup>. The results, presented in Appendix B, support a linear association between monsoon season rainfall and the risk of stunting and severe stunting; negative anomalies are associated with a reduced risk of stunting and severe stunting and, on the opposite, positive anomalies with an increased risk (see Table B1 and Fig. B1 in Appendix B). In a second robustness check, we account for potential migration, which would lead to mismatching of the rainfall data with children's location. For this purpose, we exclude from the sample non-permanent residents and children whose mothers did not live at the current place of residence a year before the child was born. The results remain robust to our baseline models (Table B2 in Appendix B).

### 5.2. Critical periods of exposure to rainfall anomalies

We additionally investigate specific periods of exposure to rainfall anomalies which might be critical to children's physical development. For this purpose, we run a series of logistic regressions with stunting as

<sup>4</sup>Some literature suggests that the risk of stunting in India increases with droughts, see for example (Kumar et al., 2016).

**Table 3**  
Impacts of rainfall anomalies on the odds of being stunted and severely stunted, children aged 0–5.

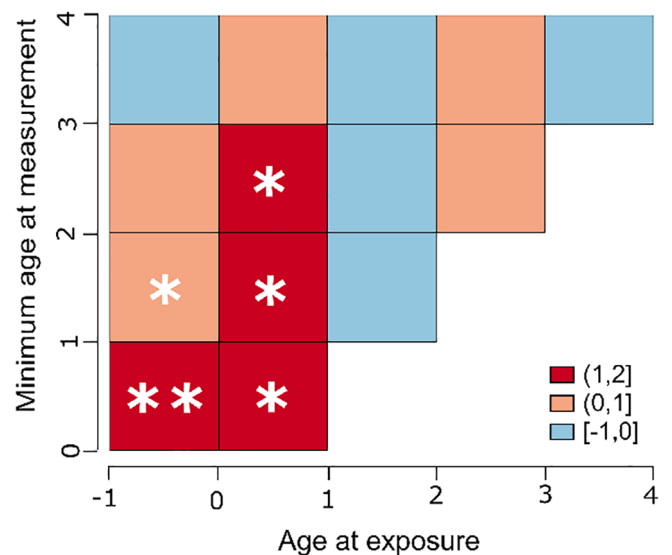
	Stunted (OR)		Stunted (OR)		severely stunted (OR)		severely stunted (OR)	
Average rainfall anomalies	1.16***	(0.03)	1.17***	(0.03)	1.20***	(0.03)	1.21***	(0.03)
<b>Individual characteristics</b>								
Sex (ref. = female)								
male			1.07***	(0.01)			1.13***	(0.02)
Twin (ref. = no)								
yes			1.51***	(0.11)			1.58***	(0.14)
Birth order			1.08***	(0.01)			1.08***	(0.01)
<b>Maternal characteristics</b>								
Age at giving birth			0.98***	(0.002)			0.98***	(0.002)
Education (ref. = no)								
primary			0.90***	(0.02)			0.84***	(0.02)
secondary			0.76***	(0.01)			0.70***	(0.02)
higher			0.58***	(0.02)			0.57***	(0.03)
<b>Household characteristics</b>								
Wealth (ref. = poorest)								
poorer			0.84***	(0.02)			0.77***	(0.02)
middle			0.70***	(0.02)			0.60***	(0.02)
richer			0.55***	(0.02)			0.48***	(0.02)
richest			0.42***	(0.02)			0.38***	(0.02)
Number of under 5 children			1.05***	(0.01)			1.04***	(0.01)
Household head (ref. = male)								
female			1.02	(0.02)			0.98	(0.02)
Caste (ref. = other)								
scheduled caste and tribe			1.28***	(0.03)			1.26***	(0.04)
other backward class			1.14***	(0.02)			1.12***	(0.03)
Residence (ref. = urban)								
rural			0.94**	(0.02)			0.92**	(0.03)
Observations	220,823		220,823		220,823		220,823	
Pseudo R <sup>2</sup>	0.06		0.08		0.05		0.08	

Notes: \* $p < 0.05$ , \*\* $p < 0.01$ , \*\*\* $p < 0.001$ . Average rainfall anomalies are measured from the in-utero period up until the time of the interview. Age splines and fixed effects for month of birth, month of interview, year of interview and district are included but not displayed. Robust standard errors are reported in parenthesis. Standard errors are clustered at the district level. Sampling weights are applied.

the outcome variable and a heavy rainfall event during a single period of exposure as the main explanatory variable. Heavy rainfall event is defined as a rainfall anomaly in a given monsoon season which exceeds one standard deviation. The measure of rainfall anomalies is dichotomized this way to isolate the effects of monsoon season rainfall above the norm, i.e. extreme precipitation and flood events. We additionally translate the results into average marginal effects (AME), which show the change in stunting prevalence due to a heavy rainfall event. This allows for a more intuitive interpretation of the results.

We present the results of this analysis in Fig. 3, where the x-axis indicates the age at which the child was exposed to a heavy rainfall event. The y-axis indicates the minimum age to which the sample is restricted. For example, a minimum age at measurement 3 means that the sample was restricted to children aged 3 to 5 years old. The idea behind this exercise is to identify whether the effect of rainfall anomalies is long-lasting. Each rectangle represents a separate regression model with a specified age at impact and minimum age at measurement.

We identify that exposure to heavy rainfall events is most critical for physical growth when the child was in infancy (age between 0 and 1) and in utero (in the womb), see Fig. 3. Experiencing a heavy rainfall event during these early life periods is associated with an increase in the probability of stunting of about one percentage point. The effect can be long-lasting, with children that have been exposed to a heavy rainfall event in infancy still being too short compared to their peers at age two and three. At age four the association is no longer observed, which could be due to catch-up growth or selective survival of the healthier children. We do not find an association between the risk of stunting and exposure to heavy rainfall events at age two and above.



**Fig. 3.** Impact of heavy rainfall events on child stunting (percentage points change in stunting prevalence). The figure shows average marginal effects (AME) based on logistic regression models calculated separately for each minimum each age at measurement and age at exposure. Heavy rainfall events are dummy variables, which take the value of 1 if total monsoon season rainfall in a given year is 1 or more standard deviations above the long-term mean (1970–2016), and 0 otherwise. Age splines and fixed effects for month of birth, month of interview, year of interview and district are included. Detailed results are available in Table A5 in the Appendix. Sampling weights are applied. \* $p < 0.05$ , \*\* $p < 0.01$ .

**Table 4**  
Impacts of rainfall anomalies on the odds of being stunted by period of birth, children aged 0–5.

	Period of birth		
	Pre-monsoon season (ORs)	Monsoon season (ORs)	Post-monsoon season (ORs)
Rainfall anomaly in infancy	1.04** (0.02)	1.05*** (0.02)	1.03 (0.02)
Observations	81,731	75,226	56,760
Pseudo R <sup>2</sup>	0.06	0.07	0.06

Notes: \*\* $p < 0.01$ , \*\*\* $p < 0.001$ . Age splines and fixed effects for month of birth, month of interview, year of interview and district are included but not displayed. Robust standard errors are reported in parentheses. Standard errors are clustered at the district level. Sampling weights are applied.

Given that rainfall in India follows a strong seasonal pattern – higher in the monsoon months and lower during the rest of the year, the associated health risks for children may also be pronounced during specific times of the year. To check whether this is the case, we run the baseline model separately for children born before the start of the monsoon season (months January to May), during the monsoon season (months June to September), and in the post-monsoon period (months October to December). Our main variable of interest is rainfall anomalies experienced in the first year of life. The results presented in Table 4 show that excessive rainfall increases the risk of stunting for children during the monsoon season or the months before, while children born later in the year are not affected. The seasonal effect on stunting is possibly due to the fact that new-borns are particularly vulnerable to infections, which are likely to increase during the episodes of high precipitation. In contrast, children born after the monsoon season are less likely to contract water- and vector-borne diseases, which may give them an advantage in the first months of life. However, we cannot establish a causal relationship due to potential sources of bias, such as selective fertility.

### 5.3. Role of sociodemographic factors

Regardless of climate condition, children born to certain socio-demographic groups are more likely to be undernourished than others. Table A1 in the Appendix shows that children born to poor households, uneducated mothers and socially disadvantaged classes have on average lower HAZ scores and are more likely to be stunted and severely stunted. For example, half of children born to women with no formal education are stunted, whereas this share is only 21% among women with higher education. Similarly, stunting prevalence is 10 percentage points higher in rural areas than in urban areas.

Based on the conceptual framework described in Section 2, it is likely that climate shocks exacerbate such disadvantages in nutrition status, while certain individual and household characteristics may shield children off from the negative health consequences of rainfall shocks. Here we empirically investigate whether this is the case by comparing the likelihood of stunting due to rainfall anomalies among different population subgroups. The predicted probabilities of stunting in Fig. 4 are obtained from the regression models which include an interaction term between the average rainfall anomalies variable and sociodemographic characteristics; detailed results are presented in Tables A2 and A3 in Appendix A.

While boys are generally more likely to be stunted than girls, the risk of stunting increases faster for girls for each standard deviation increase in rainfall anomalies (Fig. 4, Panel A). The female advantage in nutrition status disappears when monsoon rainfall is one standard deviation above the norm. Social class also appears to be an important determinant of climate-related vulnerabilities – excessive rainfall significantly increases the risk of stunting for children born to scheduled

castes and tribes (SC & ST) and other backward classes (OBC), but it does not seem to affect children from other, not socially disadvantaged, groups (Fig. 4, Panel B). Similarly, children living in rural areas face a sharp increase in the risk of stunting due to heavy rainfall, while for urban children excess rainfall does not significantly increase their health risks (Fig. 4, Panel C).

We also investigate differences in climate-related vulnerabilities by mother's level of education and household wealth status. We find that children born to less educated mothers and poorer families are particularly vulnerable to rainfall fluctuations during the monsoon season (Fig. 4, Panels D and E). In contrast, children whose mothers have higher education or whose families are in the top wealth quintile seem to be unaffected.

In addition, we group mother's level of education and family's wealth status to assess their relative importance in reducing climate-related vulnerabilities (Fig. 4, Panel F). Previous literature has argued that investment in female education can yield a series of positive externalities beyond improved income (Lutz, 2017; Lutz et al., 2014). This includes vulnerability reduction and enhancing adaptive capacity. Correspondingly, we find that children born to wealthier families but less educated mothers exhibit almost identical probability of being stunted as children born to poorer families but better educated mothers at every level of rainfall anomalies. This suggests that education can somewhat compensate for lower wealth in reducing children's vulnerability to rainfall-induced undernutrition. Education also seems to complement the effect of wealth, with children born to educated and wealthy households having the lowest probability of being stunted at every level of rainfall anomalies.

### 5.4. Role of water, sanitation and hygiene

We additionally explore the role of water, sanitation and hygiene in reducing children's risk of stunting due to rainfall fluctuations. The predicted probabilities of stunting in Fig. 5 are obtained from a regression model with an interaction term between the climate measure and each of the three WASH variables. We do not find evidence that the presence of clean water source on the premise or improved sanitation facilities reduces the risk of stunting due to excessive rainfall (Fig. 5, Panels A and B). Children living in a household with an improved sanitation facility or direct access to clean water face the same increase in the risk of stunting due to rainfall anomalies as children living in households without such amenities. However, we find that improved hygiene practices are associated with a reduced risks of stunting (Fig. 5, Panel C). At higher levels of rainfall anomalies, the risk of stunting does not show significant increase for children whose mothers report improved hygiene but it does show significant increase for children whose mother report poor hygiene.

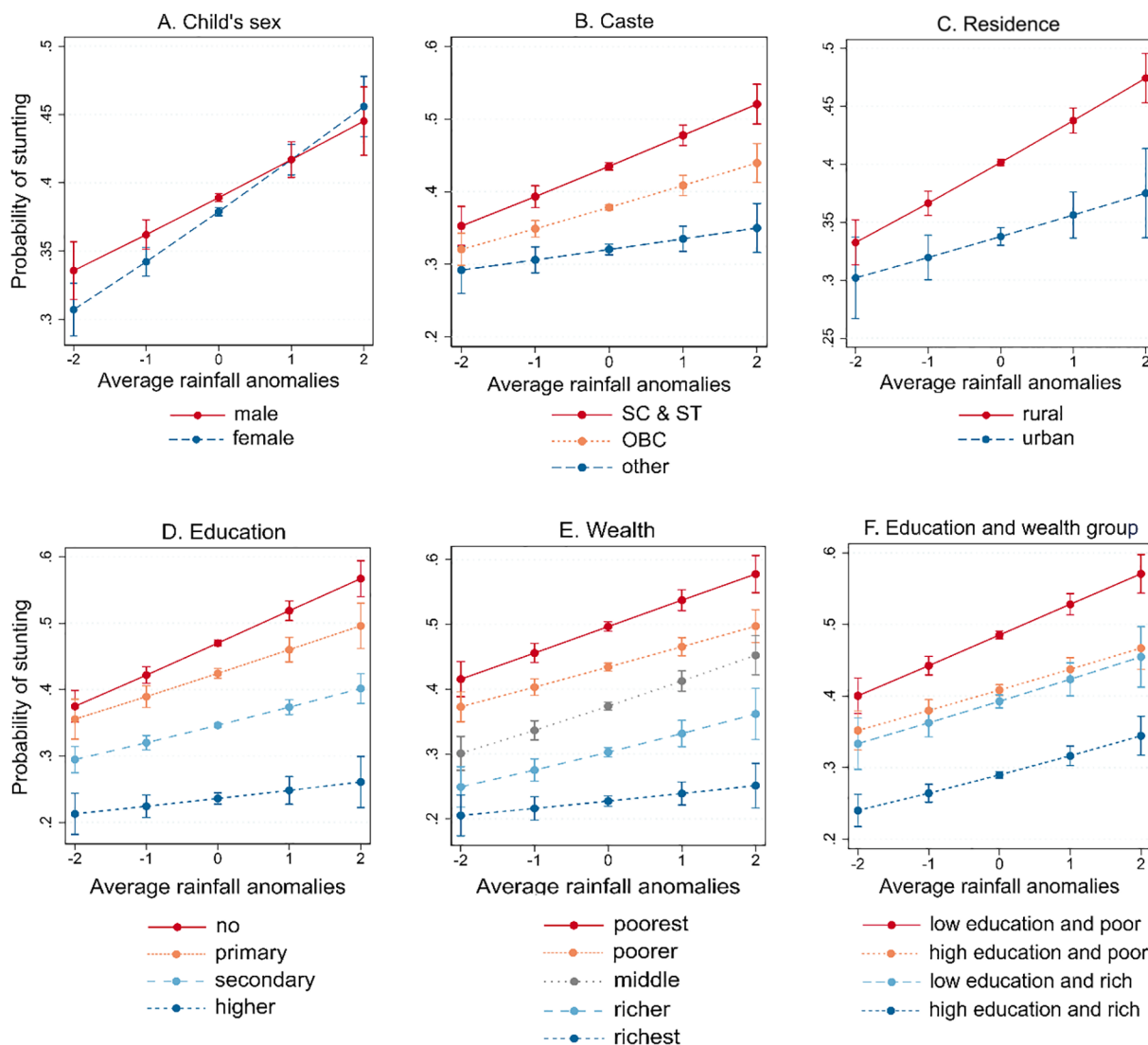
### 5.5. Decomposing the effect of education on child stunting

The above analysis provides consistent evidence supporting the role of mother's education in protecting against the adverse impacts of rainfall shocks on child health. While we are not able to establish a causal link between education and child nutrition with the available data, the association is strong, and it is not driven by differences in wealth. To examine the potential underlying mechanisms, we conduct a mediation analysis, testing the importance of various factors that can help explain the channels through which mother's education contributes to reducing the risk of child stunting.

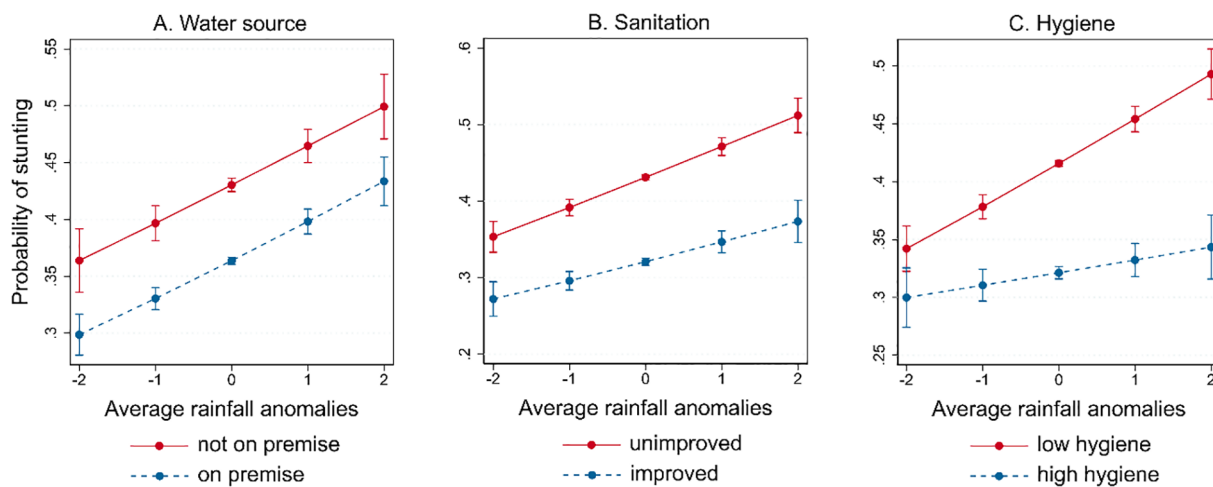
Table 5 reports the results of the KHB analysis<sup>5</sup> described in Section 4. First, the effect of education of child stunting is estimated with the

<sup>5</sup> The effect sizes did not change substantially when we included all mediators together compared to including one at a time. That is why we present the model with all mediators included together.





**Fig. 4.** Impacts of rainfall anomalies on stunting by sociodemographic group, children aged 0–5. Figures show predicted probabilities and 95% CIs. Average rainfall anomalies are measured from the in-utero period up until the time of the interview. See Tables A2 and A3 in Appendix A for detailed results.



**Fig. 5.** Impacts of rainfall anomalies on stunting by WASH category, children aged 0–5. Figures show predicted probabilities and 95% CIs. Average rainfall anomalies are measured from the in-utero period up until the time of the interview. See Table A4 in the Appendix for detailed results.

**Table 5**  
KHB model – Decomposing the effect of mother’s education on stunting.

	Education (primary vs. no)	Education (secondary vs. no)	Education (higher vs. no)
Reduced model	0.81*** (0.05)	0.60*** (0.03)	0.30*** (0.02)
Full model	0.86** (0.05)	0.68*** (0.03)	0.37*** (0.03)
Effect change in %	25.56%	24.22%	17.48%
<i>Components</i>			
Health-specific knowledge	18.73%	18.76%	13.86%
Health-care utilisation	6.23%	5.04%	2.98%
Female empowerment	0.60%	0.43%	0.65%

Notes: \* $p < 0.05$ , \*\* $p < 0.01$ , \*\*\* $p < 0.001$ . Obs.: 29,763. Pseudo  $R^2$ : 0.09. Detailed results for each group of mediator variables are available in Table C3. Cell entries for total, direct and indirect effects are odds ratios with robust standard errors in parenthesis. Age splines and fixed effects for month of birth, month of interview, year of interview and district are included but not displayed. Standard errors are clustered at the district level. 87% of observations were dropped compared from the baseline model due to missing data for HIV knowledge and female empowerment.

standard logit model. In a second step, we add the potential mediators to the model and observe changes in the coefficients for education. The KHB method, designed for non-linear nested models, determines the explanatory power of each mediator, presented in Table 5 as the percentage change in the education coefficient after controlling for the relevant mediator.

Since mother’s education is a categorical variable, Table 5 shows a coefficient for each level of education with “no education” being the reference category. The reduced model shows the total effect of mother’s education on child stunting before the inclusion of potential mediators. For example, children whose mothers have primary education are nearly 20% less likely to be stunted than children whose mothers have no formal education. Similarly, having secondary education reduces the odds of stunting by 40% and having tertiary education reduces them by 70%.

The full model, reported underneath, includes all mediator variables, thus the coefficients for education show the direct effects on the risk of stunting only. This analysis shows that primary education reduces the odds of stunting by 14% only, while secondary and higher education reduce them by 32% and 63%, respectively. The difference between the coefficients in the reduced and the full models gives the indirect effect of education on child stunting which runs through the various mediators.

About a quarter of the mitigating effect of primary and secondary education and 18% of the effect of higher education on the risk of stunting can be explained by the mediator variables. Mediators relating to health-specific knowledge and health-care utilisation are particularly important. Some of the effect of education also operates through female empowerment but to much a lesser extent.

## 6. Discussion and conclusions

We show that exposure to excessive rainfall during the monsoon months elevates the risk of child stunting in India. Our findings complement previous research, which has found a positive association between flood exposure and child undernutrition in the South Asian region (del Ninno and Lundberg, 2005; Gaire et al., 2016; Muttarak and Dimitrova, 2019; Rodriguez-Llanes et al., 2016, 2011). We do not find evidence that dry monsoon weather increases the risk of undernutrition in India, as suggested in Kumar et al. (2016). One main difference compared to our study is that Kumar et al. (2016) use data on weight-

for-age (WAZ) for a nationally representative sample of children to measure undernutrition. WAZ reflects a combination of chronic and acute malnutrition, therefore, it is likely that the authors capture the short-term effects of droughts on children’s weight, whereas we focus on the long-term effects of rainfall shocks on children’s growth trajectories. More research is needed to understand the different mechanisms through which droughts and floods affect children’s health.

More importantly, we identify various demographic and socio-economic factors determining the degree of vulnerability to rainfall shocks in India. First, we demonstrate that the most critical periods of exposure to excessive rainfall are in utero (when the child was in the womb) and infancy (age 0 to 1). The disadvantage is persistent; children who were exposed to heavy rainfall during these early periods were still too short compared to their peers at age two and three. These findings are in line with the developmental origins of health and disease hypothesis, which states that environmental conditions before and shortly after birth can have long-lasting impact on health during childhood and even adulthood (Mandy and Nyirenda, 2018). Nutritional interventions should therefore be focused at pregnant women and infants, especially when extreme climate events occur, in order to prevent the long-term harm to child growth and development.

Second, we find evidence of female disadvantage in nutrition status when household face external shocks. The results show that girls are at a higher risk of stunting due to rainfall anomalies than boys, even though the former are on average less likely to be stunted (Khan et al., 2019; Wamani et al., 2007; Wells, 2000). Our findings seem to reflect gender-based discrimination in feeding practices and general negligence towards girls in households struggling with financial insecurity during climatic shocks. In India, preferences for male children are persistent, with around 22% of female deaths under age five attributed to gender discrimination (Guilmoto et al., 2018). It is likely that these practices remain and possibly become more strongly entrenched during climatic shocks when households are struggling with reduced resources. Avoiding such female disadvantages from early life is highly important since health deprivations can later be transmitted to their children.

Third, social class remains a strong source of inequalities in India also when it comes to vulnerability to climate shocks. We find that children born in socially disadvantaged classes have an increased risk of stunting due to heavy monsoon season rainfall, while in other social groups this risk is unchanged. This suggests that rainfall shocks can deepen existing inequalities. In India, households who belong to scheduled groups are more likely to live in poverty (Boroah, 2005; Gang et al., 2008), which translates into the lack of access to clean water and sanitation facilities, higher chance of experiencing food insecurity and restricted access to healthcare. Socially disadvantaged groups are also more likely to live in high risk zones, such as slums located in areas prone to landslide and flood-prone low-lying coastal areas. A study on flood risks and vulnerability in Bangladesh found that poor households are not only less adaptive to floods, but also more likely to experience floods in the first place and less likely to receive assistance after the disaster (Brouwer et al., 2007). Social and economic inequalities therefore need to be considered when designing policy interventions to ensure that resources are placed where they are most needed.

Fourth, we highlight the important role of mother’s education in protecting child health during climate shocks. Children born in poor households but to educated mothers face almost the same risk of stunting due to rainfall excess as children born in wealthy households but to uneducated mothers. Our finding lends support to the wider policy discourse which advocates for investment in universal education, particularly female education in reducing vulnerability and enhancing

adaptive capacity to climate change (Lutz, 2017; Lutz et al., 2014).

The results of the KHB analysis suggest that better health knowledge and health-care utilisation are the main channels through which higher education of the mother translates into better health outcomes for her child. These findings are in line with previous research, which shows that educated mothers are more likely to acquire health-specific knowledge, either directly through schooling (Heaton et al., 2005; Kovsted et al., 2002) or through improved literacy which gives them additional access to information (Glewwe, 1999; LeVine et al., 2012). Educated mothers are usually the first to utilise health services as well (Greenaway et al., 2012; Heaton et al., 2005). All of the above have been directly linked to better health outcomes for their children. Although female empowerment seems to play a lesser role, possibly because the effect on child health is indirect, previous research shows that education gives women greater bargaining power and higher autonomy to take decisions concerning their child's health (Carlson et al., 2015; Cunningham et al., 2015).

Finally, we show that ensuring basic hygiene conditions is a crucial channel to improve child health against the negative consequences of climate extremes. Poor hygiene of the mother is found to be strongly associated with increased risk of stunting due to rainfall excess. In contrast, lack of improved sanitation facilities and water on the premise do not seem to play a role. Poor hygiene remains a serious problem in rural India, where it is associated with increased risk of stunting in young children (Rah et al., 2015). Providing a clean home environment is crucial for the survival of children and their physical development (Ngure et al., 2014). In low- and middle-income countries, 5.5% of child deaths under the age of five are attributed to inadequate WASH conditions (Prüss-Ustün et al., 2014). The deterioration of hygienic conditions due to climate change is likely to pose an additional pressure. This is also evident from the 2018 floods in Kerala, where a noticeable rise in communicable diseases was detected once the water started to recede. Our findings suggest that introducing behavioral changes, in particular better hygiene practices among caregivers, could reduce some of the disease burden on young children posed by climate change.

There are certain limitations of this study which need to be considered. The use of cross-sectional data does not allow us to establish a causal relationship between rainfall anomalies and child stunting. Moreover, we cannot observe a direct link between the different mediators for education in the KHB analysis and children's risk of stunting due to climate shocks. It may be the case that such mediating factors play a lesser role during climate shocks. Additional evidence is needed to understand which aspects of education are most important for reducing climate-related vulnerabilities. Moreover, most of the control and mediator variables used in the analysis are self-reported, which means they are subject to misreporting. Lastly, severe undernutrition increases the risk of infant mortality. Therefore, our sample may be biased due to the higher chance of survival of the healthier children. If this is the case, our analysis is likely to underestimate the negative effect of rainfall shocks on child health. To fully understand the burden on children from extreme climate events, future studies should consider

child mortality as well.

In conclusion, we find evidence that excessive rainfall increases the risk of stunting in India. Most importantly, we show that health outcomes depend not only on the severity of the climate shock but also on pre-existing vulnerabilities. Children born in disadvantaged castes, poorer households and to less educated mothers are more likely to be affected than children born in less socially disadvantaged groups. The results of the present study warn on the urgent need to aid children particularly infants and pregnant women in flood affected areas. Apart from immediate nutritional interventions, measures which could strengthen populations' adaptive capacities in the long run include promoting education, particularly health and hygiene knowledge, improving access to healthcare, reducing economic and social inequalities and addressing gender-based discrimination practices.

In particular, our findings suggest that investment in women's education can significantly reduce vulnerability in the context of climate change. While increasing wealth would help reduce the impact of floods on children's health, investment in human capital may prove more sustainable and bring longer-lasting benefits. In view of the international sustainable development agenda, investing in education can speed up progress towards other SDG targets in the areas of nutrition (SDG2), inequalities (SDG10), climate action (SDG13) and even female empowerment (SDG5) (Bengtsson et al., 2018; Lutz, 2017; Lutz et al., 2014; Sachs et al., 2019). Targeted interventions and investments seem even more important considering the limited resources of low- and middle-income countries to contain the threats posed by climate change.

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## CRediT authorship contribution statement

**Anna Dimitrova:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing - original draft. **Raya Muttarak:** Conceptualization, Investigation, Methodology, Writing - original draft.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Descriptive statistics and results tables

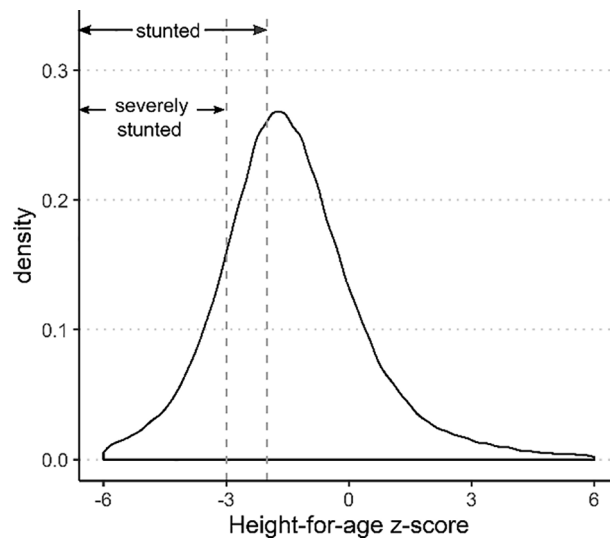


Fig. A1. Sample distribution of HAZ scores, children aged 0–5. The vertical dashed reference lines indicate the  $-2$  and  $-3$  z-score thresholds which correspond with stunting and severe stunting. Biologically implausible scores ( $HAZ < -6$  or  $HAZ > 6$ ) were removed from the sample.

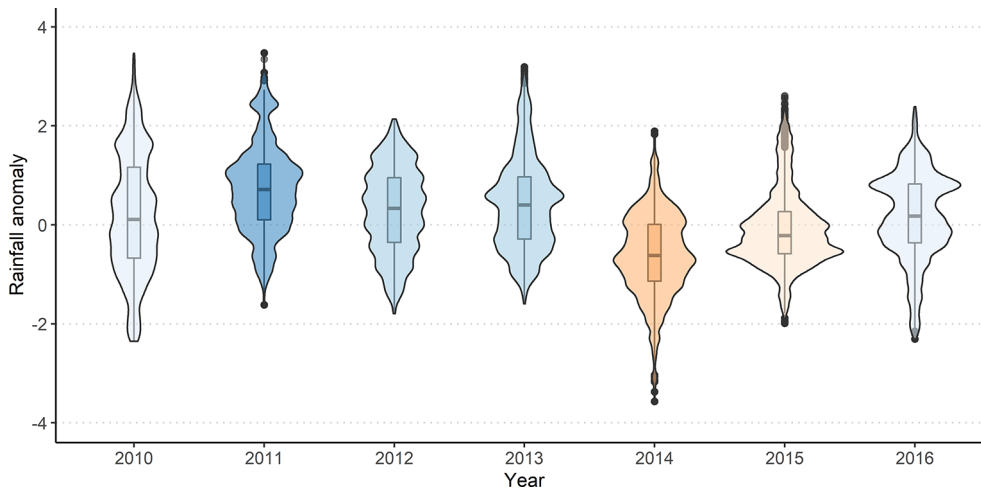


Fig. A2. Violin and box-plots showing the distribution of rainfall anomalies from 2010 to 2016. Rainfall anomalies are calculated as deviations in monsoon season rainfall from the location-specific long-term mean (1970–2016). Each point represents a separate location. Colors indicate years which were drier (orange) or wetter (blue) on average compared to the long-term mean. Darker shades indicate greater number of locations with wet/dry spells. Most years display wetter than usual monsoon conditions, with 2011 being the wettest and 2014 the driest years overall for the 2010–2016 period. Source: Own calculations based on CRU TS 3.25.

Table A1  
Mean HAZ score and prevalence of stunting and severe stunting by sociodemographic characteristics and WASH, children aged 0–5.

	Mean HAZ	% stunted	% severely stunted
Sex of child			
female	-1.41	38.28	16.02
male	-1.47	39.16	17.25
Caste			
other	-1.18	31.26	12.00
SC & ST	-1.60	43.13	19.46
OBC	-1.44	38.89	16.71
Residence			
urban	-1.18	31.54	12.38
rural	-1.54	41.46	18.29
Education			
no	-1.86	50.57	25.10
primary	-1.63	43.29	18.05
secondary	-1.26	33.16	12.46
higher	-0.75	21.10	7.67
Wealth			
poorest	-1.89	51.47	25.96
poorer	-1.63	43.67	18.81

(continued on next page)

**Table A1** (continued)

	Mean HAZ	% stunted	% severely stunted
middle	-1.39	36.94	14.04
richer	-1.15	29.72	10.71
richest	-0.82	22.44	7.94
Education and wealth group			
low education and poor	-1.88	51.33	25.42
high education and poor	-1.52	40.35	16.68
low education and rich	-1.53	40.15	16.15
high education and rich	-1.03	27.43	9.68
Water			
not on premise	-1.57	41.79	18.36
on premise	-1.37	37.01	15.70
Sanitation			
unimproved	-1.66	44.74	20.40
improved	-1.12	29.78	22.09
Hygiene			
low	-1.57	42.66	19.23
high	-1.19	30.82	11.49

Note: Sampling weights applied.

**Table A2**  
Impacts of rainfall anomalies on stunting by sociodemographic groups, children aged 0–5.

	Model 1		Model 2		Model 3	
	(OR)		(OR)		(OR)	
Sex: anomaly						
female: anomaly	1.19***	(0.03)				
male: anomaly	1.14***	(0.03)				
Sex (ref. = female)						
male	1.05***	(0.01)				
Caste: anomaly						
Other: anomaly			1.08	(0.04)		
SC & ST: anomaly			1.21***	(0.04)		
OBC: anomaly			1.15***	(0.03)		
Caste (ref. = other)						
SC & ST			1.70***	(0.04)		
OBC			1.32***	(0.03)		
Residence: anomaly						
urban: anomaly					1.10	(0.05)
rural: anomaly					1.17***	(0.03)
Residence (ref. = urban)						
rural					1.34***	(0.03)
Age splines	YES		YES		YES	
District FEs	YES		YES		YES	
Month of birth	YES		YES		YES	
Month of interview	YES		YES		YES	
Year of interview	YES		YES		YES	
Observations	220, 823		220,823		220, 823	
Pseudo R <sup>2</sup>	0.06		0.06		0.06	

Notes: \* $p < 0.05$ , \*\* $p < 0.01$ , \*\*\* $p < 0.001$ . Age splines and fixed effects for month of birth, month of interview, year of interview and district included but not displayed. Anomaly denotes average rainfall anomalies measured from the in-utero period up until the time of the interview. Robust standard errors reported in parentheses. Standard errors clustered at the district level. Sampling weights applied.

**Table A3**  
Impacts of rainfall anomalies on stunting by sociodemographic groups, children aged 0–5.

	Model 1		Model 2		Model 3	
	(OR)		(OR)		(OR)	
Education: anomaly						
no: anomaly	1.23***	(0.03)				
primary: anomaly	1.16***	(0.04)				
secondary: anomaly	1.13***	(0.03)				
higher: anomaly	1.07	(0.05)				
Education (ref. = no)						
primary	0.82***	(0.02)				
secondary	0.58***	(0.01)				
higher	0.33***	(0.01)				
Wealth: anomaly						

(continued on next page)

**Table A3 (continued)**

	Model 1	Model 2	Model 3
poorest: anomaly		1.19***	(0.04)
poorer: anomaly		1.14***	(0.03)
middle: anomaly		1.18***	(0.04)
richer: anomaly		1.16**	(0.05)
richest: anomaly		1.07	(0.06)
Wealth (ref. = poorest)			
poorer		0.77***	(0.02)
middle		0.59***	(0.01)
richer		0.42***	(0.01)
richest		0.28***	(0.01)
Education-wealth:			
anomaly			
low education and poor: anomaly			1.20*** (0.03)
high education and poor: anomaly			1.14*** (0.03)
low education and rich: anomaly			1.15** (0.05)
high education and rich: anomaly			1.14*** (0.04)
Education-wealth (ref. = low-poor)			
high education and poor			0.72*** (0.01)
low education and rich			0.67*** (0.02)
high education and rich			0.41*** (0.01)
Age splines	YES	YES	YES
District FEs	YES	YES	YES
Month of birth	YES	YES	YES
Month of interview	YES	YES	YES
Year of interview	YES	YES	YES
Observations	220,823	220,823	220,823
Pseudo R <sup>2</sup>	0.07	0.07	0.07

Notes: \* $p < 0.05$ , \*\* $p < 0.01$ , \*\*\* $p < 0.001$ . Age splines and fixed effects for month of birth, month of interview, year of interview and district included but not displayed. Anomaly denotes average rainfall anomalies measured from the in-utero period up until the time of the interview. Robust standard errors reported in parenthesis. Standard errors clustered at the district level. Sampling weights applied.

**Table A4**

Impacts of rainfall anomalies on stunting by WASH category, children aged 0–5.

	Model 1	Model 2	Model 3
	(OR)	(OR)	(OR)
Water: anomaly			
not on premise: anomaly	1.16***		(0.04)
on premise: anomaly	1.17***		(0.03)
Water (ref. = not on premise)			
on premise	0.74***		(0.02)
Sanitation: anomaly			
unimproved: anomaly		1.19***	(0.03)
improved: anomaly		1.13***	(0.03)
Sanitation (ref. = unimproved)			
improved		0.61***	(0.01)
Hygiene: anomaly			
low: anomaly			1.18*** (0.03)
high: anomaly			1.05 (0.04)
Hygiene (ref. = low)			
high			0.64*** (0.01)
Age splines	YES	YES	YES
District FEs	YES	YES	YES
Month of birth	YES	YES	YES
Month of interview	YES	YES	YES
Years of interview	YES	YES	YES
Observations	217, 456	217,724	220,754
Pseudo R <sup>2</sup>	0.06	0.06	0.06

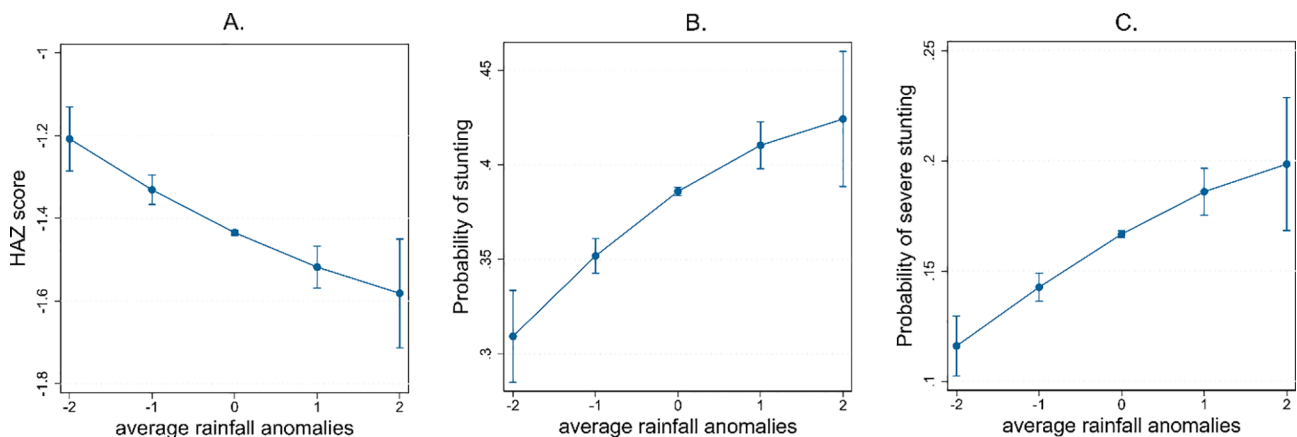
Notes: \* $p < 0.05$ , \*\* $p < 0.01$ , \*\*\* $p < 0.001$ . Age splines and fixed effects for month of birth, month of interview, year of interview and district included but not displayed. Anomaly denotes average rainfall anomalies measured from the in-utero period up until the time of the interview. Robust standard errors reported in parentheses. Standard errors clustered at the district level. Sampling weights applied.

**Table A5**  
Impacts of extreme precipitation anomalies on stunting by age at exposure and minimum age at measurement.

	Age ≥ 0	Age ≥ 1	Age ≥ 2	Age ≥ 3
anomaly ≥ 1 in utero	0.012** (0.004)	0.010* (0.004)	0.003 (0.004)	-0.000 (0.005)
anomaly ≥ 1 at age 0	0.011* (0.005)	0.011* (0.005)	0.011* (0.005)	0.005 (0.006)
anomaly ≥ 1 at age 1		-0.003 (0.005)	-0.003 (0.005)	-0.007 (0.006)
anomaly ≥ 1 at age 2			0.005 (0.008)	0.005 (0.008)
anomaly ≥ 1 at age 3				-0.004 (0.012)

Notes: \* $p < 0.05$ , \*\* $p < 0.01$ , \*\*\* $p < 0.001$ . Cell entries are average marginal effects (AME) based on logistic regression models calculated separately for each minimum each age at measurement and age at exposure. Age splines and fixed effects for month of birth, month of interview, year of interview and district included but not displayed. Robust standard errors reported in parenthesis. Standard errors clustered at the district level. Sampling weights applied.

**Appendix B. Robustness analysis**



**Fig. B1.** Predicted HAZ score (A) and probabilities of being stunted (B) and severely stunted (C) with 95% CIs based on Table A6, children aged 0–5. Average rainfall anomalies measured from the in-utero period up until the time of the interview.

**Table B1**  
Impacts of rainfall anomalies on HAZ score, stunting and severe stunting – testing for non-linearity in the effects, children aged 0–5.

	HAZ (OLS coef.)	Stunted (OR)	Severely stunted (OR)
Average rainfall anomalies	-0.09*** (0.02)	1.14*** (0.03)	1.18*** (0.04)
Average rainfall anomalies <sup>2</sup>	0.01 (0.01)	0.98 (0.015)	0.97 (0.02)
Observations	220,823	220,823	220,823
(Pseudo) R <sup>2</sup>	0.11	0.06	0.05

Notes: \* $p < 0.05$ , \*\* $p < 0.01$ , \*\*\* $p < 0.001$ . Age splines and fixed effects for month of birth, month of interview, year of interview and district included but not displayed. Sampling weights applied. Average rainfall anomalies measured from the in-utero period up until the time of the interview. Robust standard errors reported in parentheses. Standard errors clustered at the district level. Sampling weights applied.

**Table B2**  
Impacts of rainfall anomalies on HAZ score, stunting and severe stunting – controlling for migration, children aged 0–5.

	HAZ (OLS coef.)	Stunted (OR)	Severely stunted (OR)
Average rainfall anomalies	–0.10*** (0.02)	1.16*** (0.03)	0.17*** (0.03)
Observations	157,610	157,610	157,610
Pseudo R <sup>2</sup>	0.11	0.06	0.05

Notes: \* $p < 0.05$ , \*\* $p < 0.01$ , \*\*\* $p < 0.001$ . Sample excludes non-permanent residents and children whose mothers have relocated since the child was in-utero. Age splines and fixed effects for month of birth, month of interview, year of interview and district included but not displayed. Average rainfall anomalies measured from the in-utero period up until the time of the interview. Robust standard errors reported in parentheses. Standard errors clustered at the district level. Sampling weights applied.

**Appendix C. Mediation analysis**

Table C1 provides an overview of variables used in the KHB (mediation) analysis. These are grouped into “health-specific knowledge”, “health-care utilization” and “female empowerment”. Questions on HIV knowledge and female empowerment were addressed only to a sub-sample of randomly selected women. As a result, 87% of observations were dropped in the mediation analysis compared to the baseline model. To ensure that the reduced sample is not subject to a selection bias, we produced summary statistics for the main variables of interest, displayed in Table C2 below. We can see that the full and reduced samples are comparable. Women with no and secondary education are somewhat over-represented in the reduced sample, however, the differences are not substantial. The distribution of mediator variables is comparable between the full and reduced samples as well.

**Table C1**  
Description and summary statistics of mediator variables.

Variable	Description	Range
<i>Health-specific knowledge</i>		
HIV knowledge	Respondent has heard of HIV (yes = 1; no = 0)	0–1
Mosquito net use	Household has mosquito bed net for sleeping (yes = 1; no = 0)	0–1
Hygiene	Proper disposal of child’s stool (yes = 1; no = 0)	0–1
<i>Health-care utilisation</i>		
Antenatal care visits	Made at least 1 antenatal care visit during latest pregnancy (yes = 1; no = 0)	0–1
Delivery	Gave birth in a health facility under the supervision of a trained professional (yes = 1; no = 0)	0–1
Child vaccination	Child has received full vaccination (yes = 1; no = 0)	0–1
<i>Female empowerment</i>	Respondent participates in decision making concerning health-care, large household purchases and visits to friends and relatives and does not justify wife beating in any situation (yes = 1; no = 0)	0–1

**Table C2**  
Descriptive statistics for main variables of interest – full and reduced sample.

	Full sample (n = 220,823)		Reduced sample (n = 29,763)	
	Mean (Proportion)	Std. Dev.	Mean (Proportion)	Std. Dev.
Stunted	0.38	0.49	0.35	0.48
Education				
no	0.31	0.46	0.27	0.45
primary	0.15	0.35	0.14	0.34
secondary	0.45	0.50	0.48	0.50
higher	0.09	0.29	0.11	0.32
HIV knowledge	–	–	0.73	0.44
Mosquito net use	0.42	0.49	0.42	0.49
Hygiene	0.33	0.47	0.37	0.48
Antenatal care visits	0.81	0.39	0.83	0.37
Delivery	0.51	0.50	0.59	0.49
Child vaccination	0.12	0.33	0.16	0.37
Female empowerment	–	–	0.37	0.48



**Table C3**  
KHB model: Decomposing the effect of mother's education on stunting.

	Education	Education	Education
	(primary vs. no)	(secondary vs. no)	(higher vs. no)
Reduced	0.81*** (0.05)	0.60*** (0.03)	0.30*** (0.02)
Full	0.86** (0.05)	0.68*** (0.03)	0.37*** (0.03)
Effect change in %	25.56%	24.22%	17.48%
<b>Components</b>			
<b>Health-specific knowledge</b>	<b>18.73%</b>	<b>18.76</b>	<b>13.86</b>
HIV knowledge	12.45%	10.89%	6.48%
Mosquito net use	0.31%	0.23%	0.13%
Hygiene	5.97%	7.64%	7.25%
<b>Health-care utilisation</b>	<b>6.23</b>	<b>5.04</b>	<b>2.98</b>
Antenatal care visits	-0.24%	-0.15%	-0.08%
Delivery	6.12%	4.76%	2.83%
Child vaccination	0.35%	0.43%	0.23%
<b>Female empowerment</b>	<b>0.60</b>	<b>0.43</b>	<b>0.65</b>

Notes: \* $p < 0.05$ , \*\* $p < 0.01$ , \*\*\* $p < 0.001$ . Obs.: 29,763. Pseudo  $R^2$ : 0.09. Cell entries for total, direct and indirect effects are odds ratios with robust standard errors reported in parentheses. Standard errors are clustered at the district level. Age splines and fixed effects for month of birth, month of interview, year of interview and district included but not displayed.

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