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Stunted from the start: Early life weather conditions and child undernutrition in Ethiopia

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ABSTRACT

This paper examines the relationship between weather conditions and child nutrition in Ethiopia. We link data from four rounds of the Ethiopia Demographic and Health Survey to high-resolution climate data to measure exposure to rainfall and temperature *in utero* and during early life. We then estimate a set of multivariate regression models to understand how weather conditions impact child stunting, an indicator of sustained early life undernutrition. We find that greater rainfall during the rainy seasons in early life is associated with greater height for age. In addition, higher temperatures *in utero*, particularly during the first and third trimesters, and more rainfall during the third trimester, are positively associated with severe stunting, though stunting decreases with temperature in early life. We find potential evidence for a number of pathways underlying the weather-child nutrition relationship including agricultural livelihoods, heat stress, infectious disease transmission, and women's time use during pregnancy. These findings illuminate the complex pathways through which climate change may influence child health and should motivate additional research focused on identifying the causal mechanisms underlying these links.

1. Introduction

Stunting, or low height for age, is the most prevalent form of undernutrition globally, affecting nearly one in four children under age five (de Onis and Branca, 2016; Perkins et al., 2017). Rates of stunting have declined worldwide over the past several decades, yet the prevalence remains high in Sub-Saharan Africa, where nearly 34% of children under five are stunted (UNICEF, 2019). In addition, Sub-Saharan Africa is the only region to have experienced an increase in the number of stunted children over the past decade (FAO et al., 2018; UNICEF, 2019). In response to slow progress on improving nutrition in many world regions, the United Nations has focused a Sustainable Development Goal (SDG) on ending all forms of malnutrition worldwide by 2030 (United Nations, 2015). Yet, through direct and indirect effects on health and livelihoods, climate change has the potential to undermine future reductions in stunting and other forms of malnutrition (FAO et al., 2018; Haines and Patz, 2004; McMichael, 2013; Zhao et al., 2017).

Sub-Saharan Africa is particularly vulnerable to changing climatic conditions, as over 60% of the workforce is employed in agriculture and 96% of cropland is rainfed (FAO, 2012; Field et al., 2014; World Bank, 2015). The Intergovernmental Panel on Climate Change (IPCC) predicts with high confidence that future climate change in the region will exacerbate existing stresses on water resources, reduce crop yields, and increase malnutrition, particularly among children (Niang et al., 2014). It is therefore critical to better understand how climatic conditions affect child nutrition in order to develop effective policies to combat undernutrition in a warmer, more variable world.

Stunting is an indicator of chronic, sustained undernutrition often reflecting a child's health and nutrition *in utero* and during the first two years of life (de Onis and Branca, 2016). Stunting in early life is associated with long-term negative health and socioeconomic impacts including reduced neurocognitive function, lower educational attainment, shorter adult height, and lower wages and lifetime earnings (e.g., Dewey and Begum, 2011; Perkins et al., 2017; Victora et al., 2008). Stunting has intergenerational impacts as well, as pregnancies among stunted women are linked to a higher risk of maternal mortality, low birthweight, and neonatal death (Black et al., 2008; Victora et al., 2008). Further, child malnutrition has been found to be the underlying cause of 53% of deaths among young children, as it increases the risk of mortality from other illnesses including diarrhea, acute respiratory illness, malaria, and measles (Caulfield et al., 2004; Rice et al., 2000).

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Chronic childhood undernutrition is therefore a critical barrier to improving future health and well-being, and it can trap affected populations in an intergenerational cycle of poverty.

This paper examines the impacts of weather conditions on stunting among approximately 23,000 children aged one through four years in Ethiopia, a country in which 85% of the population works in agriculture and nearly 50% of rural children experience undernutrition (Endris et al., 2017; USAID, 2014). We ask how rainfall and temperature experienced *in utero* and during a child's life affect height-for-age z-score (HAZ), stunting (HAZ < -2), and severe stunting (HAZ < -3). Specifically, we examine average weather conditions across the prenatal period and throughout a child's early life, as well as conditions during each trimester *in utero* and each season in early life, to determine whether critical periods of exposure exist.

2. Mechanisms underlying the weather-child nutrition relationship

In climate-health research there are three commonly explored pathways that underlie the relationship between weather conditions and child nutrition: agricultural livelihoods, infectious disease transmission, and heat stress. More favorable rainfall and temperature conditions lead to greater crop and livestock production, which improves household income and food security. Adverse weather conditions exacerbate diarrheal diseases or vector-borne diseases such as malaria and dengue fever. Prolonged exposure to high temperatures can cause heat stress, which has important implications for fetal development.

Extensive research has discovered that exposure to droughts or floods in early life is associated with slower growth and an increased risk of stunting (e.g., Bahru et al., 2019; del Ninno and Lundberg, 2005; Hoddinott and Kinsey, 2001; Rodriguez-Llanes et al., 2011). Other studies have found positive relationships between early life rainfall and height over both the short and long term (Grace et al., 2012; Maccini and Yang, 2009). Taken together, these studies suggest that greater rainfall is beneficial to young children and that both negative and positive rainfall shocks can negatively impact child nutrition. The primary mechanism postulated is that adverse rainfall conditions negatively impact agricultural production and income, which in turn decreases food availability for young children during critical periods of development. However, while rainfall effects are well studied, research on early life temperature and child nutrition remains extremely limited (Amegah et al., 2016).

A number of studies have found that exposure to low rainfall, flooding, or high temperatures during pregnancy is negatively associated with birthweight and positively associated with preterm birth (Bakhtsiyarava et al., 2018; Basu et al., 2018; Carolan-Olah and Frankowska, 2014; Grace et al., 2015; Rocha and Soares, 2015; Rosales-Rueda, 2018). Both low birthweight and preterm birth are risk factors for childhood stunting, and the prenatal period is therefore critical for child development and health outcomes (Akombi et al., 2017; Danaei et al., 2016). Exposure to adverse weather conditions *in utero* can thus affect both short- and long-term child health outcomes.

For example, experiencing sub-optimal rainfall or temperature conditions during pregnancy may impact maternal and fetal nutrition, leading to intrauterine growth restriction. A study in Vietnam found that maternal weight gain during early pregnancy was an important predictor of birthweight, which suggests that undernutrition during this period is a critical barrier to fetal growth (Young et al., 2017). Thus, the first trimester of pregnancy may be a critical period for the effect of maternal nutrition on birthweight, and in turn on stunting. Heat stress during pregnancy can also damage the placenta, decreasing fetal nutrition and leading to low birthweight (Basu et al., 2018). Further, extreme heat exposure in the third trimester can trigger early labor, potentially leading to preterm birth. Researchers have hypothesized a few possible mechanisms for this: heat may initiate pre-term labor if a pregnant woman becomes dehydrated, which decreases blood flow to the uterus, or heat stress can prompt the release of labor-inducing hormones (Basu et al., 2010; Carolan-Olah and Frankowska, 2014).

Weather conditions may also impact child nutrition through a maternal and early childhood infectious disease pathway. Higher temperatures, heavy rainfall events, and flooding are associated with a higher risk of diarrheal diseases, which can affect nutrition among both pregnant women and young children (Bandyopadhyay et al., 2012; Levy et al., 2016). Malaria infection during pregnancy is associated with an increased risk of low birthweight, as malaria parasites tend to accumulate in the placenta, affecting its structure and function (Umbers et al., 2011). Further, malaria exposure during early childhood is associated with an increased risk of stunting in Ethiopia (Gari et al., 2018). Approximately 60% of Ethiopians currently live in areas endemic for malaria (Girum et al., 2019), and climate change is expected to increase malaria transmission in the highlands, as warming temperatures become more favorable for the survival and reproduction of disease vectors and parasites (Endo and Eltahir, 2020; Siraj et al., 2014). However, risk is expected to remain low among those living at elevations above 2200 m, even under a high emissions scenario (Endo and Eltahir, 2020).

Another potential – yet understudied – pathway between weather conditions and child undernutrition is through women's time use during pregnancy. In rural areas of low- and middle-income countries, women are central to agricultural production as well as domestic tasks such as fetching water, and these physically demanding activities can put stress on pregnant women. Data from Uganda and Burkina Faso suggest that seasonal variation exists in labor demands among pregnant women, with the rainy season requiring more time engaged in agricultural labor and the dry season straining women due to high temperatures (Grace et al., 2017; MacVicar et al., 2017). Droughts can also increase energy expenditure among pregnant women if they must travel longer distances to collect water for drinking and cooking. Studies in rural India and Brazil have found that engaging in physically demanding work during pregnancy is negatively associated with birthweight (Lima et al., 1999; Rao et al., 2003). Thus, weather conditions may impact birthweight, and in turn stunting, through their effects on pregnant women's agricultural and domestic labor.

We build upon the existing literature in three ways. First, we examine how both rainfall and temperature affect child stunting. Second, we examine the effects of weather conditions *in utero* and during early life, as well as during each trimester and each season of life. And third, we propose an additional potential pathway linking weather conditions to child stunting beyond agricultural production, heat stress, and infectious disease transmission – time use among pregnant women. Fig. 1 presents a conceptual model of the pathways linking climatic conditions to child stunting, particularly for rural, agricultural populations. Climatic conditions directly and indirectly affect agricultural livelihoods, infectious disease transmission, heat stress, and women's time use, all of which may play a role in child stunting. Our conceptual model also accounts for the fact that many additional micro- and macro-level factors impact stunting independent of weather, such as gender, education, and social welfare policies.

3. The Ethiopian context

Ethiopia is the second most populous country in Africa, with a population of approximately 109 million (World Bank, 2019). The country has experienced rapid economic growth over the past decade, but 27% of Ethiopians still live on less than $1.90 per day (World Bank, 2019). Nutrition has improved as well, however 38% of children under five remain stunted, 18% are severely stunted, and 22% of women of childbearing age are undernourished (Central Statistical Agency (CSA) [Ethiopia] and ICF, 2016). In Ethiopia, the most common risk factor for stunting among young children is fetal growth restriction (which results in low birthweight) and preterm birth (Danaei et al., 2016). Thirty-four percent of stunting is attributable to these factors, compared to 14%

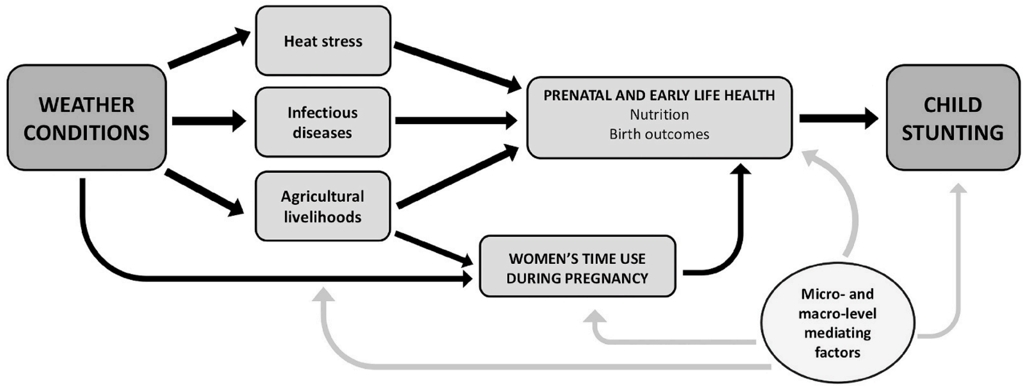

Fig. 1. Conceptual model of the linkages between weather conditions and child stunting.

attributable to child nutrition and infection, indicating that conditions *in utero* are key determinants of early childhood stunting (Danaei et al., 2016).

Seventy-nine percent of Ethiopians live in rural areas, and agriculture plays a central role in the country's economy, with smallholder farmers producing 95% of all agricultural products (FAO, 2019; World Bank, 2018). Nearly all agriculture in the country is rainfed, as irrigation technology supports just 3% of food crops (Machado Mendes and Paglietti, 2015). Ethiopia varies greatly in terms of topography and climate, with average annual rainfall ranging from 300 mm in lowland arid regions to 2000 mm in the highlands (Viste et al., 2013). Pastoral and agro-pastoral livelihoods dominate in the hot arid and semi-arid lowlands, and 12 million Ethiopians rely on livestock herding or a mixture of livestock and crop production (Woodeneh, 2016). However, the majority of Ethiopians reside in the cooler and wetter highlands, where livelihoods center on the production of crops including teff, maize, and coffee (Evangelista et al., 2013). See Fig. 2 for a map of Ethiopia including elevation.

Ethiopia has two rainy seasons: *kiremt*, which typically lasts from June to September, and *belg*, which typically runs from February to May (Seleshi and Zanke, 2004). The dry season, *bega*, extends from October to January. Crops grown during *kiremt* make up 90–95% of total annual production, while *belg* crops account for the remainder (Bezabih and Di Falco, 2012). Rainfall during *kiremt* and *belg* is essential for crop production, while excessive rain during the *bega* dry season can hinder harvesting activities, damage crops, and cause crop diseases such as powdery mildew (Evangelista et al., 2013; National Meteorological Services Agency, 2005). Ethiopia experiences episodic droughts and dry spells, with large spatial variation in their timing and severity (Viste et al., 2013). Since the mid-1970s, *belg* and *kiremt* rains have declined by 15–20% in southern, southwestern, and southeastern Ethiopia (Funk et al., 2012), and *kiremt* rainfall has decreased in the heavily populated eastern highlands of Oromia and Amhara (Brown et al., 2017).

Climate projections for Ethiopia predict an annual warming of 2.2 °C by the 2050s, which will lead to a greater frequency of heat waves and higher rates of evaporation (Conway and Schipper, 2011). Climate models predict an increase in *kiremt* precipitation in the central Highlands and northern Great Rift Valley and a decrease throughout southern Ethiopia (Li et al., 2016). While maize yields may benefit from climate change in parts of Ethiopia over the short term (Araya et al., 2015), even conservative emissions scenarios predict overall reductions in cereal production by 2050 (Evangelista et al., 2013).

Our analysis builds on a significant previous literature investigating the consequences of large-scale shocks for food security and nutritional status in Ethiopia. Yamano, Alderman, and Christiaensen (2005) found that community-level crop damage in 1995–1996 predicted lower child heights, though food aid to the community was protective. Dercon and Porter (2014) examined the long-term consequences of the 1984 drought, revealing that young adults who were aged 12–36 months at the time of the crisis were significantly shorter than children exposed at other ages. Hagos et al. (2014) used data from administrative regions covering 1996–2004 to show that area-level stunting increased with rainfall and low temperatures, though without accounting for the age or other characteristics of the children exposed. Three papers using data from the Young Lives project also revealed that food insecurity experienced *in utero*, shortly after birth, and via community-level drought shocks all undermine child health outcomes (Beshir and Maystadt, 2020; Hy der Baloch and Behrman, 2016; Miller, 2017). Most recently, Sohnesen (2019) compared various measures of severity for the 2015 drought, finding them to be poorly correlated with each other and also with household consumption, and Hirvonen et al. (2020) similarly found that the 2015 drought had limited impacts on child undernutrition.

Taken together, these studies reveal that Ethiopian children can be vulnerable to climate shocks, but that recent droughts did not lead to nutritional losses, leaving the current state of vulnerability rather unclear. Further, previous studies have largely ignored temperature – a central risk to health and well-being under climate change. To provide clarity, we expand this literature by using nationally-representative data on children born over a 20-year time period, by examining weather exposures at different stages of development, and by directly investigating the effects of local temperature, a key threat from climate change that has not been adequately examined.

4. Methods

4.1. Data

To understand the relationship between weather and child stunting in Ethiopia, we link data from the Demographic and Health Surveys Program (DHS) to detailed temperature and precipitation data. The DHS collects nationally-representative nutrition and health information for women aged 15–49 and children under five using a multi-stage cluster sampling approach. We use four rounds of the Ethiopia DHS, conducted in 2000, 2005, 2011, and 2016. Each round contains geographic coordinates of the sampling clusters as well as child nutrition measures including anthropometry (height/length and weight). In 2000, 2011, and 2016, anthropometric measures were taken for all children under five, while in 2005, measures were taken from a subsample of children (Central Statistical Agency [Ethiopia] and ORC Macro, 2006). The DHS contains an array of individual-, household-, and community-level variables, which enable us to control for underlying differences in stunting across sub-populations.

Our analytic sample consists of all children between the ages of one and five at the time of the survey. Children in the sample were born as early as 1995 and as late as 2015. We exclude twins/multiples, children who did not reside with the respondent, and those whose mother was a visitor in the interviewed household. Our analytic sample includes

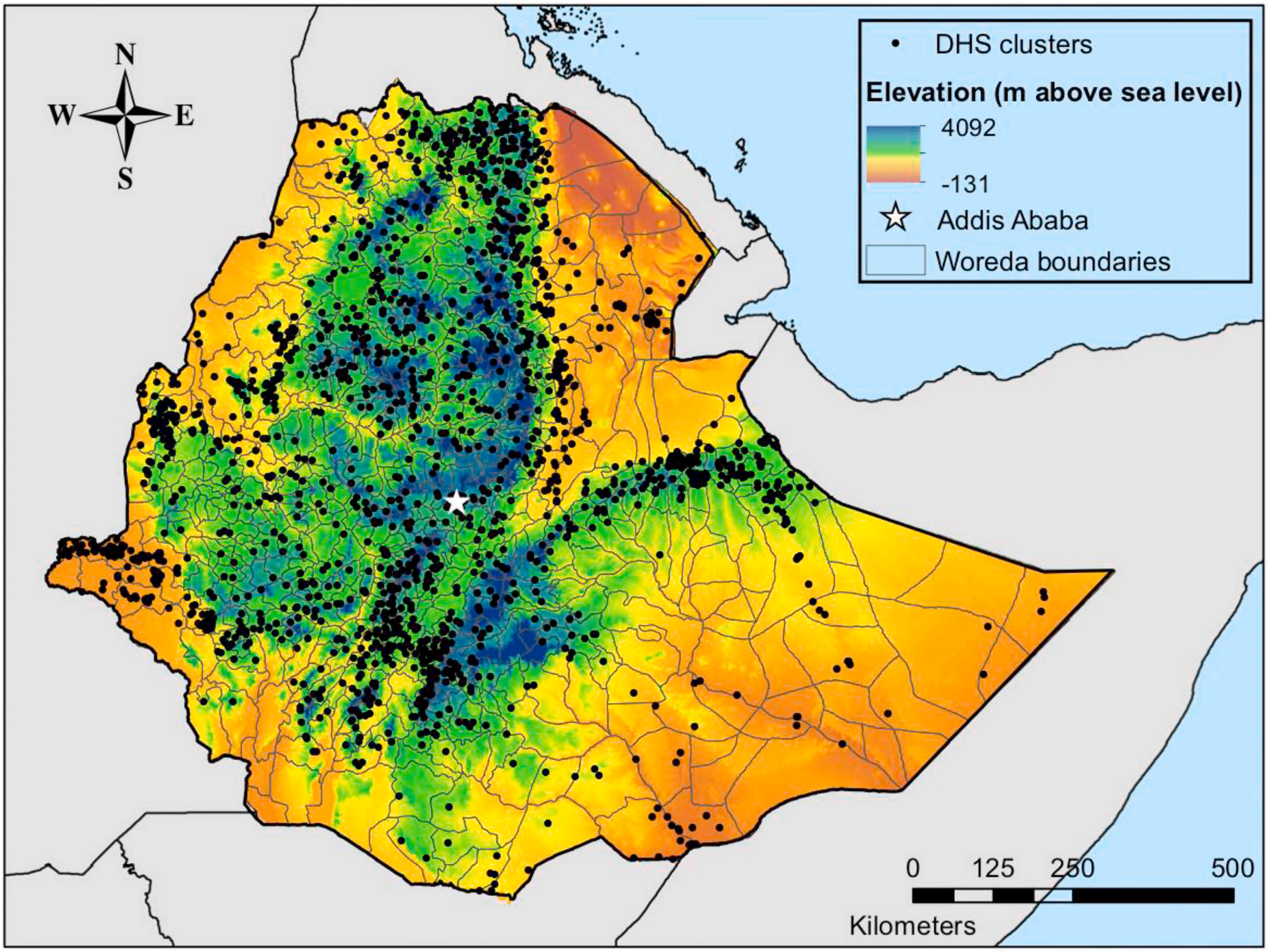

Fig. 2. Map of Ethiopia including DHS clusters and woreda boundaries.

23,026 children. The anthropometric outcome variables are height-for-age z-score (HAZ), stunting (HAZ ≤ -2), and severe stunting (HAZ ≤ -3). Stunting, defined according to the WHO Child Growth Standards, is an indicator of long-term sustained undernutrition (WHO, 2006).

We use precipitation data from the Climate Hazards group Infrared Precipitation with Stations (CHIRPS) and newly available temperature data from the Climate Hazards Center Infrared Temperature with Stations ($CHIRTS_{max}$) (Funk et al., 2019b, 2015). Both CHIRPS and $CHIRTS_{max}$ provide 0.05° (~5 km) gridded data using a combination of weather station and satellite data. CHIRPS data perform well in Ethiopia (Bayissa et al., 2017; Dinku et al., 2018) and are widely used by USAID and in research for food security monitoring (Bakhtsiyarava et al., 2018; Davenport et al., 2017). $CHIRTS_{max}$ data are effective for monitoring extreme temperatures in Ethiopia and have been shown to be more accurate for assessing climatic conditions in Africa than the commonly used Climate Research Unit (CRU) T_{max} data (Funk et al., 2019b). We link climate data to DHS data at the cluster level using GPS points. To ensure confidentiality, the DHS randomly displaces the GPS locations of rural clusters by between 0 and 5 km (with 1% of clusters displaced by up to 10 km) (Burgert et al., 2013). To account for this, we create a 10-km buffer around each cluster and average the climatic conditions for all grid cells contained within that buffer.

Our weather measures consist of mean maximum daily temperature (°C) and mean monthly rainfall (cm) averaged across the child's prenatal period as well as early life (birth through the time of the survey). We also measure average conditions during each trimester *in utero* and as well as for each season (*kiremt*, *bega* and *belg*) from the time of birth through the survey month in order to account for changing vulnerabilities during gestation as well as the timing of weather exposures during the seasonal calendar (FEWS NET, 2013). Finally, we also use the GPS locations to identify the *woreda* (third level administrative unit) in which the cluster was located in 2015 in order to apply time-consistent woreda fixed effects as described below (ArcGIS, 2015). A small fraction of clusters will be placed in the wrong woreda by this procedure because of the GPS offset, but the estimated fixed effects for adjacent woredas are likely to be similar given the high spatial autocorrelation in contextual characteristics (Spielman and Yoo, 2009).

4.2. Analysis

We estimate a set of multivariate regression models for each of the three nutrition outcomes based on temperature and precipitation conditions. We use ordinary least squares (OLS) to model HAZ and binary logistic regression to model the likelihood of stunting and severe stunting. Our modeling approach factors in the DHS survey design by accounting for the primary sampling unit (cluster), stratified sampling (by region and urban/rural status), and sampling weight.

To account for underlying differences in nutrition and climate between children in Ethiopia's approximately 530 *woredas* and across time, we include fixed effects for each *woreda* and survey year (see Fig. 2 for DHS cluster locations and *woreda* boundaries). The inclusion

Table 1
Descriptive statistics for DHS variables used in analysis (N = 23,026 children).

	Mean/proportion	SD	Min	Max
Nutrition outcomes:				
HAZ	−2.11	1.58	−6	5.94
Stunted	0.54		0	1
Severely stunted	0.28		0	1
Child characteristics:				
Sex [1 = female]	0.49		0	1
Age in months	36	14	12	59
Birth order	4	2.58	1	16
Birth season:				
Belg	0.33		0	1
Kiremt	0.32		0	1
Bega	0.35		0	1
Maternal characteristics:				
Mother has any education	0.26		0	1
Mother's age	30	7	15	49
Mother's height (cm)	1567	63.15	465	1995
Cluster characteristics:				
Elevation (m above sea level)	2012	506	−92	3979

of these fixed effects accounts for all time-invariant factors at the *woreda* level and all time-varying factors at the national level. This is important because weather exposures are likely to be confounded by a large number of local, time-invariant characteristics (such as a topography and soils) as well as national time-varying characteristics (such as state policies and urbanization) which are difficult to control for in the absence of fixed effects. The coefficients are statistically identified by remaining within-*woreda* variation in weather over time, which is exogenous and can be interpreted as a natural experiment (Nordkvelle et al., 2017).

To account for additional factors known to affect child growth, we include a set of child controls (sex, age in months, birth order, and birth season) as well as maternal controls (mother's education, age, and height). Both linear and squared terms for the child's age in months are included to account for the nonlinear relationship between age and HAZ across early childhood (Victora et al., 2010). With these controls included, the results can be interpreted as comparing two children with the same characteristics living in the same *woreda* at the same time period but with differing climate exposures.

The first set of models focuses on average rainfall and temperature conditions during the prenatal period as well as across a child's life from birth through the survey month. We then estimate a set of models that focuses on average climatic conditions during each trimester *in utero*, controlling for average monthly rainfall and temperature from birth through the survey month. Next, we estimate a set of models focusing on seasonal conditions during early life, controlling for average prenatal rainfall and temperature. Lastly, we estimate a set of models predicting the likelihood of severe stunting based on nonlinear weather conditions during the same periods of time. We then calculate predicted probabilities of severe stunting for significant quadratic weather variables, or for significant linear weather variables if there is no evidence of a quadratic relationship, holding all other variables at their means.

4.3. Sensitivity analyses

Finally, we perform a set of sensitivity analyses. The first accounts for the potential role of migration in mis-specifying exposure to weather variables. The 2000, 2005, and 2016 DHS rounds contain information on the length of time an interviewed woman lived in the study cluster. We limit our analysis to children of women who lived in the cluster for at least a year before their child's birth in order to ensure that the children were exposed to the weather conditions of their cluster *in utero* as well as early life. Only 5% of women migrated to the cluster during or after the pregnancy of the sample child, and the results (Appendix Table A2) are consistent with the main models.

Next, we test the extent to which the climate data source affects our findings by repeating the first analysis using CRU temperature and precipitation data (Harris et al., 2020). CRU is a long-established and widely used climate data source but is of much coarser resolution than CHIRPS/CHIRTS_{max} at 0.5°. The results (Appendix Table A3) are consistent with the main models. We then examine the role that average minimum daily temperature plays by repeating the first analysis using CRU T_{min} data. The results (Appendix Table A4) are consistent with the main models, though generally we find that T_{min} is a weaker predictor of stunting and severe stunting than T_{max}. Lastly, we repeat the main analysis without the use of sampling weights and our results are consistent with the main models (Appendix Table A5).

Finally, an important limitation to using HAZ is the risk of bias due to the potential for misreporting of a child's birthdate (Larsen et al., 2019). We estimate a model that excludes children born in August and September (the end/beginning of the Ethiopian calendar) to account for a linear HAZ gradient across the year due to random reporting of month of birth (Appendix Table A6). The temperature results are robust to this specification. Next, we estimate a model that excludes children aged 24, 25, 36, 37, 48, and 49 months to account for rounding down a child's age to age in completed years, thereby overestimating HAZ for some children (Appendix Table A7). The results are consistent with the main models.

5. Results

Table 1 presents descriptive statistics for children in the analytic sample. Stunting is common, with 54% of children stunted, 28% severely stunted, and a mean HAZ of −2.11. Fertility among mothers is high, with an average birth order of four, and only 26% of mothers have completed any formal schooling. Table 2 presents descriptive statistics for the climate data used in the model, indicating substantial variation in temperature and rainfall conditions experienced by children.

Table 3 presents results from models predicting HAZ as well as the likelihood of stunting and severe stunting based on average weather conditions *in utero* and during early life. We find that during the prenatal period, hotter conditions are negatively associated with HAZ and positively associated with stunting and severe stunting, while wetter conditions are negatively associated with HAZ. For example, a 1 °C increase in average prenatal temperature is associated with a 28% increase in the odds of severe stunting. The average within-*woreda*

Table 2
Descriptive statistics for weather variables used in analysis (N = 23,026 children).

	Mean/proportion	SD	Min	Max
Average prenatal weather:				
Rainfall	9.54	3.76	0.37	25.01
Temperature	26.06	2.74	18.94	42.21
Prenatal weather by trimester:				
First trimester rainfall	9.36	7.27	0.00	46.36
First trimester temperature	26.15	2.96	17.25	44.55
Second trimester rainfall	9.46	7.26	0.00	45.43
Second trimester temperature	26.13	2.97	18.40	44.39
Third trimester rainfall	9.25	7.21	0.00	43.10
Third trimester temperature	26.16	3.00	17.00	44.55
Average weather, birth through current age:				
Rainfall	8.90	2.81	0.87	18.59
Temperature	26.22	2.70	19.55	40.63
Seasonal weather, birth through current age:				
Belg rainfall	7.19	3.61	0.63	22.69
Belg temperature	27.58	2.87	20.48	41.40
Kiremt rainfall	16.50	6.99	0.05	40.77
Kiremt temperature	25.10	2.92	17.81	43.86
Bega rainfall	3.86	2.42	0.13	15.56
Bega temperature	25.85	2.63	19.45	40.48

Note: Rainfall is measured in centimeters and temperature is measured in degrees Celsius.

Table 3
HAZ, stunting, and severe stunting based on average prenatal and early life weather.

	Model 1	Model 2	Model 3
	HAZ	Stunting	Severe stunting
	Coefficient	Odds Ratio	Odds Ratio
Prenatal weather:			
Rainfall	−0.015*	1.014	1.021+
Temperature	−0.083**	1.162**	1.280***
Weather conditions from birth to current age:			
Rainfall	0.035**	0.976	0.961*
Temperature	0.070+	0.867**	0.772***
Child characteristics:			
Sex [1 = female]	0.112***	0.861***	0.842***
Age in months	−0.068***	1.095***	1.092***
Age in months squared	0.001***	0.999***	0.999***
Birth order	−0.023*	1.055***	1.050**
Birth season [belg is baseline]			
Kiremt	−0.032	0.949	0.913
Bega	−0.016	1.029	0.976
Maternal characteristics:			
Mother has any education	0.160***	0.830***	0.735***
Mother's age	0.017***	0.974***	0.981**
Mother's height	0.004***	0.994***	0.995***
Cluster characteristics:			
Elevation	−0.0002	1.0002	1.0002+
N	23,026	22,977	22,848
Wald test:			
Weather variables	3.40**	2.70*	6.16***

Note: Models include woreda and survey year fixed effects. +p < 0.1. *p < 0.05. **p < 0.01. ***p < 0.001.

standard deviation for prenatal temperature is 0.93 °C, which suggests that a 1 °C change in temperature captures, on average, a slightly greater than 1-SD change. In early life, however, more rainfall is positively associated with HAZ and negatively associated with severe stunting, and higher temperatures are negatively associated with both stunting and severe stunting.

Table 4 presents results from models based on weather conditions during each trimester *in utero,* controlling for rainfall and temperature across the child's life. Here we find that hotter temperatures in each trimester as well as wetter conditions in the third trimester are positively associated with severe stunting. Table 5 explores seasonal weather conditions across a child's early life, controlling for prenatal conditions. Rainfall is a key determinant of a child's height. Experiencing more *belg* and *kiremt* rainfall, as well as less *bega* rainfall, is associated with a greater HAZ. For example, a 1 cm increase in early life *kiremt* rainfall is associated with a 0.012-unit increase in HAZ. The average within-*woreda* standard deviation for early life *kiremt* rainfall is 3.14 cm, which suggests that a 1 cm change in rainfall captures, on average, approximately a one-third-SD change. Further, warmer temperatures during the *bega* dry season are associated with lower odds of severe stunting.

Next, we allow rainfall and temperature to affect nutrition outcomes nonlinearly by adding quadratic terms for weather to models predicting severe stunting. Appendix Table A1 indicates that prenatal temperatures, early life rainfall and temperatures, first and third trimester temperatures, and early life *bega* temperatures have significant nonlinear associations with the odds of severe stunting. To explore the

Table 4
HAZ, stunting, and severe stunting based on prenatal weather by trimester, controlling for early life weather.

	Model 4	Model 5	Model 6
	HAZ	Stunting	Severe stunting
	Coefficient	Odds Ratio	Odds Ratio
Prenatal weather by trimester:			
First trimester rainfall	−0.001	1.0003	0.998
First trimester temperature	−0.017	1.048	1.094**
Second trimester rainfall	−0.002	1.004	1.004
Second trimester temperature	−0.018	1.034	1.061*
Third trimester rainfall	−0.009*	1.010+	1.013*
Third trimester temperature	−0.014	1.055+	1.079*
Average monthly weather from birth to current age:			
Rainfall	0.027*	0.981	0.972
Temperature	0.038	0.880*	0.788***
N	23,026	22,977	22,848
Wald test:			
Weather variables	2.76**	1.64	4.10***

Note: Models include control variables and woreda and survey year fixed effects. +p < 0.1 *p < 0.05. **p < 0.01. ***p < 0.001.

Table 5
HAZ, stunting, and severe stunting based on seasonal temperature and rainfall from birth to current age, controlling for prenatal weather.

	Model 7	Model 8	Model 9
	HAZ	Stunting	Severe stunting
	Coefficient	Odds Ratio	Odds Ratio
Average seasonal weather conditions from birth to current age:			
Belg rainfall	0.033**	0.979	0.979
Belg temperature	0.105+	0.900	0.886
Kiremt rainfall	0.012*	0.989	0.993
Kiremt temperature	−0.098+	1.177*	1.149
Bega rainfall	−0.038*	1.038	1.010
Bega temperature	0.087	0.801*	0.724**
Prenatal weather:			
Rainfall	−0.017*	1.013	1.018
Temperature	−0.104**	1.183***	1.329***
N	23,026	22,977	22,848
Wald test:			
Weather variables	2.92**	1.64	4.17***

Note: Models include control variables and woreda and survey year fixed effects. +p < 0.1. *p < 0.05. **p < 0.01. ***p < 0.001.

magnitude of the relationships between weather conditions and severe stunting, Fig. 3 presents predicted probabilities of severe stunting based on significant nonlinear weather specifications as well as significant linear specifications for variables shown to have a linear association with severe stunting.

The graphs indicate that during the first and third trimesters, as average maximum daily temperatures increase above approximately 30 °C, the risk of severe stunting rises rapidly. For example, a child who experiences an average third trimester temperature of 25 °C has a 25% probability of severe stunting, while the probability increases to 53% at 35 °C. For third trimester rainfall, the probability of severe stunting is six percentage points higher for a child who experiences 25 cm of average monthly rainfall compared to one who experiences 5 cm. Early life rainfall, in contrast, is beneficial to children. A child who experiences an average of 2 cm of rainfall per month has a 35% probability of severe stunting, compared to a 25% probability for a child that experiences 14 cm. Lastly, warmer temperatures during the *bega* dry season are negatively associated with severe stunting, and the probability of severe stunting is 25 percentage points lower for a child who experiences average temperatures of 30 °C compared to one who experiences average temperatures of 25 °C.

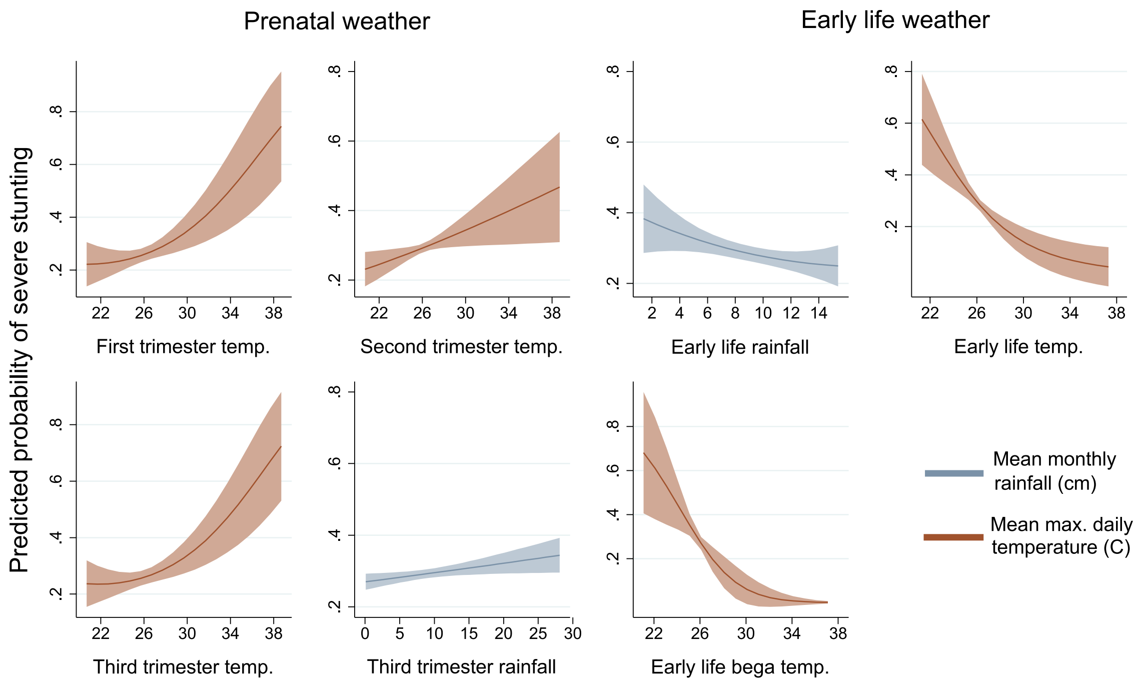

Fig. 3. Predicted probabilities of severe stunting based on prenatal and early life rainfall and temperature conditions, including 95% confidence intervals.
Note: First and third trimester temperature plots are produced from Model 11, second trimester temperature and third trimester rainfall plots are produced from Model 6, early life rainfall and temperature plots are produced from Model 10, and early life bega temperature plot is produced from Model 12.

6. Discussion

In this study, we asked whether temperature and precipitation conditions experienced *in utero* and during early life play a role in child nutrition outcomes in Ethiopia. We discovered that greater rainfall across a child's life is associated with a lower risk of severe stunting, and that more rainfall during the primary agricultural seasons (*kiremt* and *belg*) and less rainfall during the *bega* dry season are positively associated with HAZ. In contrast, greater rainfall *in utero* is negatively associated with child height, and this effect is driven by conditions during the third trimester.

Temperature is also a strong predictor of child nutrition. During the prenatal period, as average maximum daily temperatures rise above 30 °C, particularly during the first and third trimesters, the risk of severe stunting rises rapidly. Lastly, hotter temperatures in early life are negatively associated with severe stunting, and this is driven primarily by the negative effect of cool temperatures (average maximum temperatures under 26 °C), particularly during the *bega* dry season.

In our conceptual model (Fig. 1), we outlined mechanisms that may drive the relationship between rainfall and temperature conditions and child stunting. Like most large-scale quantitative analyses of weather and health, we cannot directly test these mechanisms due to data limitations (see Grace and Mikal, 2019). However, we find indirect evidence for a number of them in our study. The first mechanism relates to agricultural livelihoods. Adverse weather conditions may reduce crop and livestock production, affecting household income and food security and thereby impacting the nutrition of young children. Greater rainfall during the *kiremt* and *belg* growing seasons is likely correlated with improved crop production, while greater rainfall during the *bega* dry season may damage crops, impede harvesting activities, or lead to crop diseases such as powdery mildew, which damages stored grains (Evangelista et al., 2013; National Meteorological Services Agency, 2005). *Belg* rainfall has declined over the past few decades and climate models predict changes in *kiremt* rainfall, with increases in the central Highlands and northern Great Rift Valley and decreases throughout southern Ethiopia (Funk et al., 2019a; Li et al., 2016). Thus, there is likely to be large spatial variation in how changing rainfall conditions will impact child nutrition. Those in some regions may actually benefit from improved *kiremt* rainfall, while other regions are likely to experience increasing rates of stunting associated with declining rainfall as well as more frequent and severe droughts.

In Ethiopia, adverse birth outcomes (low birthweight and preterm birth) are the largest risk factors for early childhood stunting (Danaei et al., 2016). Conditions a child experiences *in utero* may therefore play the principal role in shaping child nutrition. When examining prenatal weather, we find that hotter temperatures during each trimester, particularly during the first and third trimesters, are associated with an increased likelihood of severe stunting. For example, children who experienced average temperatures of 35 °C during the third trimester have a 53% predicted probability of severe stunting, compared to a 25% probability among those who experienced temperatures averaging 25 °C. In addition, more rainfall during the third trimester is positively associated with severe stunting.

The link between prenatal weather and severe stunting may result from multiple pathways, the first being heat stress. Exposure to high temperatures during pregnancy can damage the placenta or trigger early labor leading to low birthweight (Basu et al., 2018, 2010; Carolan-Olah and Frankowska, 2014). Among children in the study, approximately 8% experienced average first or third trimester temperatures above 30 °C, and climate projections for Ethiopia predict rising temperatures and a greater frequency of heat waves (Conway and Schipper, 2011). Thus, we can expect the number of children exposed to high prenatal temperatures to rise over the coming years, putting them at a greater risk of stunting.

The second pathway is through maternal infectious diseases. Higher temperatures are associated with an increased risk of diarrheal diseases, which can affect nutrition among pregnant women, thereby affecting fetal nutrition (Levy et al., 2016). Warming temperatures lead to increases in malaria transmission in the Ethiopian highlands (Siraj et al., 2014), and in areas where malaria is endemic, malaria infection during the first trimester has been linked to lower birthweight (Huynh et al., 2011). Women who experience temperatures more suitable for diarrheal diseases and malaria transmission during pregnancy may thus be more likely to give birth to low birthweight babies, who are at a higher risk of stunting.

The third pathway is through women's time use during pregnancy. Rural women in low- and middle-income countries tend to engage in physically demanding agricultural and domestic labor during their pregnancies, and studies have found a negative association between strenuous work among pregnant women and birthweight (Lima et al., 1999; Peterman et al., 2013; Rao et al., 2003). Performing strenuous tasks in hot conditions may directly impact fetal development, or may lead to increased energy expenditure, affecting fetal nutrition and growth. Thus, warmer conditions may pose a risk to child nutrition as more women will experience high temperatures during pregnancy. Further, more rainfall may increase agricultural labor demands for women, including women during later stages of pregnancy, which could result in adverse birth outcomes, and eventually in childhood stunting.

Lastly, results indicate that in a tropical highland context with predominantly temperate climates, higher temperatures in early life decrease the risk of stunting. This effect appears to be driven by a heighted risk of stunting among children who experience cool average maximum daily temperatures (22–26 °C), particularly during the *bega* dry season. Warmer temperatures reduce the risk of frost, which is a common cause of crop damage in parts of the country (Holden et al., 2004). Relatedly, warming temperatures are expected to increase the yields of some crops over the short term (Araya et al., 2015; Hadgu et al., 2015). Indeed, in the Ethiopian highlands, warmer temperatures are positively associated with vegetation greenness, which suggests that crops may have benefitted from warmer temperatures in recent years (Quetin and Swann, 2017). This beneficial effect of temperature in early life roughly balances the negative effect of temperature during the prenatal period, suggesting that Ethiopian children might be relatively protected from the adverse consequences of local warming for the near term. In the longer-term, however, as warming increases mean temperatures above the range we observe here, the costs to health are likely to mount.

The findings from this study shed light on the complex pathways through which climate change may influence child nutrition and should motivate additional research focused on identifying the causal mechanisms underlying these links. Further, the results have important implications for how we understand vulnerability to climate change in Ethiopia and in the East African highlands more broadly. The East African highlands are located across seven countries and contain 150 million people, with the population expected to double to 300 million by 2050 (Bouma et al., 2016; Himeidan and Kweka, 2012).

A large body of evidence suggests that the primary threat to human health under climate change will come from increasing temperatures (Mora et al., 2017). We find evidence that heat exposure *in utero* is a key risk factor for severe stunting in early childhood, even among populations living in the relatively cool highlands of Ethiopia, but that this risk is roughly balanced (for now) by positive effects of temperature during early life. Amid rising temperatures associated with climate change, strategies for reducing heat-related vulnerability among pregnant women in these regions should be incorporated into public health responses. Possible strategies include promoting alternatives to agricultural labor among pregnant women, particularly on hot days, through facilitating diversification into non-agricultural sources of income that can be performed in cooler, shaded areas (e.g., handicraft production) or through providing weather-based income assistance to households with pregnant women. Additionally, pregnant women should be targeted for interventions that reduce exposure to diarrheal diseases and malaria, which co-occur with high temperatures in the East African highlands. Enhancing resilience to weather conditions among pregnant women and young children is critical in order to achieve the SDG target of ending all forms of malnutrition over the coming decade.

Credit author statement

Heather Randell: Conceptualization, Methodology, Formal analysis, Writing - original draft, Visualization; Clark Gray: Conceptualization, Methodology, Writing - review & editing; Kathryn Grace: Conceptualization, Methodology, Writing - review & editing.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.socscimed.2020.113234.

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