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ORIGINAL ARTICLE

Rain, temperature, and child-adolescent height among Native Amazonians in Bolivia

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Abstract

Background: Global climate change and recent studies on early-life origins of well-being suggest that climate events early in life might affect health later in life.

Aim: The study tested hypotheses about the association between the level and variability of rain and temperature early in life on the height of children and adolescents in a foraging–farming society of native Amazonians in Bolivia (Tsimane').

Subject and methods: Measurements were taken for 525 children aged 2–12 and 218 adolescents aged 13–23 in 13 villages in 2005. Log of standing height was regressed on mean annual level and mean intra-annual monthly coefficient of variation (CV) of rain and mean annual level of temperature during gestation, birth year, and ages 2–4. Controls include age, quinquennium and season of birth, parent's attributes, and dummy variables for surveyors and villages.

Results: Climate variables were only related with the height of boys age 2–12. The level and CV of rain during birth year and the CV of rain and level of temperature during ages 2–4 were associated with taller stature. There were no secular changes in temperature (1973–2005) or rain (1943–2005).

Conclusion: The height of young females and males is well protected from climate events, but protection works less well for boys ages 2–12.

Keywords: *Weather variability, temperature, rain, Tsimane', Bolivia*

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Introduction

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Introduction

The last three decades have seen unprecedented changes in the world's level and variability of temperature and rain that likely affect health (Trenberth 2001; IPCC Working Group I 2001; Frich et al. 2002; Luterbacher et al. 2004; Meehl and Tebaldi 2004; Schar et al. 2004, Seneviratne et al. 2006; CEH 2007). Climate change might alter health through several paths, such as changes in pathogen exposure, diet, water quality, and habitat (Cole 2000). Prior studies linking climate change with health share several perspectives: (i) they focus on the effect of levels of climate variables or extreme climate events on health, (ii) among health outcomes, they focus principally on infectious diseases, (iii) they come mainly from industrial nations, (iv) they focus on adults, (v) and they pay scant attention to the stage in the life cycle in which people's health might be most vulnerable to climate perturbations (Epstein 2005; Hay et al. 2005; McMichael et al. 2006; Godoy et al. 2008; Zhou et al. 2004, 2005).

In an earlier study with adults from a foraging–farming society of native Amazonians in Bolivia (Tsimane'), we filled some of the gaps by estimating the association between (i) standing height (dependent variable) and, as explanatory variables, (ii) the mean annual rain level and the mean intra-annual variability of monthly rain during (a) gestation, (b) first year of life, and (c) years 2–5 of life (Godoy et al. 2007a). The coefficient of variation (CV = standard deviation/mean) was used to measure mean intra-annual variability of monthly rain. Among adult women, mean intra-annual variability of monthly rain during years 2–5 of life was negatively associated with height but the mean annual rain level during gestation, first year of life, and years 2–5 of life were positively associated with height. Among adult men, we found no statistically significant association between rain and height.

Here we contribute to the nascent field of research on climate change and health by building on prior research on the topic. Unlike prior studies, including our own, we focus on (a) rain and temperature rather than on just rain and (b) on children and adolescents rather than on adults. Using regression analysis, we estimate the associations between (i) the standing height of children (ages: 2–12, inclusive, born 1993–2003) and adolescents (ages: 13–23, inclusive, born 1982–1992), which we use as dependent variables, and (ii) the mean annual level of rain and temperature and the mean intra-annual variability of monthly rain during gestation, first year of life, and years 2–4 of life. We refer to gestation as age 0, birth year as age 1 ($\leq$1 year of age), and years 2–4 as ages 2–4 ($>$1 age $\leq$4).

Theoretical motivations and hypotheses

Impetus to examine rain and temperature together comes from the possibility that rain, temperature, and height might be linked. If so, then failure to include both climate variables at the same time will bias the estimate of the climate variable included in the regression. For instance, some studies suggest that height is associated with more rain (Maccini and Yang 2006; Godoy et al. 2007a) and with more temperature (Leonard et al. 2002, 2005) and that higher temperature is associated with less rain (Wilkie et al. 1999). If so, then estimates of rain on height that exclude temperature will contain a downward bias from the negative indirect effect from rain via temperature to height. Our use of both climate variables at the same time represents an improvement over earlier studies.

Impetus to examine the association between climate variables and the height of children and adolescents comes from earlier studies in rural Indonesia (Maccini and Yang 2006) and Bolivia (Godoy et al. 2007a) suggesting that rain patterns experienced early were only associated with the height of adult women. By focusing on the height of people before they reach adulthood we might explain why this is so. For instance, suppose that during childhood climate events depressed the height of boys but not the height of girls, but that during adolescence compensatory biological and cultural mechanisms came into play, allowing boys to catch up so that by adulthood one no longer found traces of the link between climate variables and height found during childhood. An analysis of the association between climate variables and the height of people before they reached adulthood would allow one to trace this type of life-cycle pattern.

We focus on both the level and the variability of climate variables because levels and variability tell different stories (Zhou et al. 2004, 2005; Hay et al. 2005). Extremes of weather aside, the level of rain and temperature experienced early in life should bear a positive association with the height of children and adolescents (*Hypothesis* 1). More rain will correlate with more food production in an agricultural economy, making more dietary energy available for growth (Alderman et al. 2006; Maccini and Yang 2006; Godoy et al. 2007a). Temperature should also correlate positively with height, but for a different reason. Comparative evidence suggests that human populations living in warmer, tropical climates have lower basal metabolic rates (BMR) than human populations living in colder climates (Roberts 1978; Henry and Rees 1991; Leonard et al. 2002, 2005). Moreover, it also appears that indigenous populations living in colder climates show slower rates of physical and reproduction maturation (Roberts 1969, 1978; Leonard et al. 1994). Thus, increased average temperature may promote greater height by allowing more metabolic energy to be allocated to statural growth, and relatively less to basal, maintenance needs. That is, at the same level of energy intake (availability), lower basal requirements allow for more dietary energy to be allocated to growth and development.

Figure 1 provides a simple representation of the proposed relationship, showing the major components of total energy requirements during childhood – (1) basal metabolic rate (BMR), (2) energy costs of daily activity (Activity), and (3) energy costs of growth (Growth).

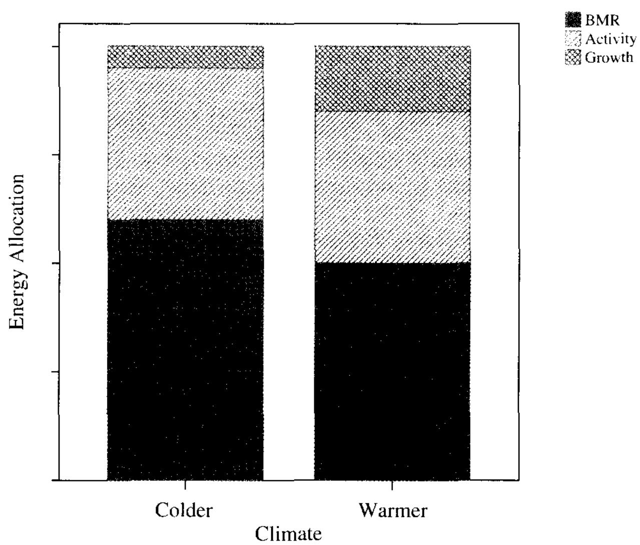

Figure 1. Major components of total energy requirements (BMR, Activity and Growth) of children living under 'colder' vs 'warmer' conditions. Assuming the same activity levels, the lower BMRs in warmer conditions are associated with allocation of greater energy for growth.

The magnitude of the differences in BMR between the warmer and colder conditions comes from work in progress by Leonard in Siberia. Assuming the same daily activity levels, individuals living in the warmer climatic conditions have lower BMRs and are able to allocation of more energy to growth.

Intra-annual variability of rain or temperature will produce fluctuations in physical activity, exposure to pathogens, consumption of clean water, and in the type and quantity of foods consumed. The fluctuations will subject the body to more wear and tear and push adaptive regulatory mechanisms to work harder and more often. Further, the biological and behavioral unpredictability of climate variability will produce additional strain on the body. Constant variability in the environment will subject the body to more and more drastic perturbations and undermine homeostasis (Godoy et al. 2005b; Lewontin and Levins 2000). Climate fluctuations will be associated with lower height because they will: (i) make it harder to stabilize food consumption and defend against infectious diseases, (ii) increase investments in immunological defense, and (iii) decrease investment in growth. Thus, we expect a negative association between intra-annual variability in rain or temperature experienced early in life and child or adolescent height (*Hypothesis* 2).

An additional, more technical, reason for including both the level and the variability of a climate variable has to do with the links between level and variability. The rationale for including the level and variability of climate variables resembles the rationale for including at the same time rain and temperature. If levels and variability intertwine, then failure to include both aspects of a climate variable will produce a biased parameter estimate for the included aspect of the climate variable. To illustrate: In the climate data we are about to present, the Pearson correlation coefficient between the level of annual rain and the intra-annual monthly CV of rain is +0.05. A bivariate regression of height for people 2–23 years of age on the CV of rain produces a slope of −28. These estimates suggest that the sign of the indirect effect from rain levels to height via the coefficient of variation of rain is negative. In this example, failure to include a measure of rain variability would produce a downward bias when estimating the effect of annual rain levels on height.

We expect height to bear a stronger association with climate events experienced during ages 2–4 than climate events experienced during gestation or birth year (*Hypothesis* 3). This will result from the protective role of both maternal physiology during pregnancy and from breastfeeding early in life (Prentice et al. 1983; Poppit et al. 1994; McDade and Worthman 1998; Ellison 2001).

We analyze each sex separately. Prior studies from rural settings of pre-industrial nations find that climate perturbations and normal weather patterns experienced early in life bore a stronger association with the height of girls than of boys (Alderman et al. 2006) and that they bore a stronger association with the height of adult women than with the height of adult men (Maccini and Yang 2006; Godoy et al. 2007a). Building on this line of empirical findings, we expect that the level and the variability of rain and temperature experienced early in life will bear a stronger association with the height of pre-adult girls than pre-adult boys (*Hypothesis* 4).

Materials and methods

Sites and sample

We collected data during June–September 2005, from nearly all people of 252 households in 13 Tsimane' villages along the Maniqui River, department of Beni. Data was gathered in a survey as part of a panel study with the Tsimane' (2002 to present). Villages differed in their proximity to San Borja (mean = 25.96 km; SD = 16.70), the only town or airport along the Maniqui River. The sample of people with complete data about themselves and their parents included 525 children (257 girls; 268 boys) 2–12 years of age (inclusive) and 218 adolescents (104 females; 114 males) 13–23 years of age (inclusive). Four surveyors who had worked in the panel study since its inception collected anthropometric and socio-economic data. Rain data (1943–2005) came from Bolivia's national aeronautical agency. Temperature data (1973–2005) came from the National Oceanic and Atmospheric Administration (NOAA), USA[1]. Rain and temperature data refer to San Borja.

Estimation strategy

We ran separate ordinary-least square (OLS) regressions for each of the following groups: (i) child girls, (ii) adolescent girls, (iii) child boys, and (iv) adolescent boys.

We split each sex into two age classes – children and adolescents – because children and adolescents have different growth trajectories and because climate variables do not have the same effect during childhood and adolescence. We did a formal test of interaction effects to assess whether treating children and adolescents as separate categories was justified. To do so, we created a dummy variable for children (1 = person was 2–12 years of age inclusive; 0 = person was 13–23 years of age inclusive) and interacted the dummy variable with each of the 12 climate variables (described later). We used OLS regressions to regress height (dependent variable) against the 12 interaction terms, the 12 climate variables, and all the covariates used in the regressions presented later. All but two of the individual interaction terms were statistically significant at the 95% confidence level or higher and all the interaction variables were jointly statistically significant ($F = 14.28$, $p = 0.0001$). We re-estimated the regressions only for females and only for males, and again found that all the interaction variables of climate × children were jointly statistically significant (females, $F = 13.34$, $p = 0.0001$; males, $F = 10.89$, $p = 0.0001$). The results of the tests for interaction effects lend technical support to our decision to split the sample into these two age classes.

We could not split the child category further into, say, infants and toddlers, because the sample size would have been too small. For instance, we had only 42 infant girls and 64 infant boys and 107 toddler girls and 90 toddler boys; the effective sample size for these four groups was smaller than these number suggest because many of these children had incomplete information on their parents. On a more substantive note, toddlers and infants would not have had complete information on climate variables for their first 4 years of life; for instance, it would have been impossible to estimate the effect of weather events during the first 3 years of life for an infant 6 months old born during 2005.

We set the top age at 23 years because Tsimane' stop growing by their early 20s (Godoy et al. 2006). When analyzing the association between climate events early in life and height, we focus on climate events experienced during gestation (age 0), birth year (age 1), and toddler years (ages 2–4). We focus on gestation and birth year because research from industrial nations suggests that events during these periods leave an imprint on health throughout life (Doblhammer and Vaupel 2001; Barker et al. 2002; Behrman and Rosenzweig 2004; Cruickshank et al. 2005). Among Tsimane', breastfeeding ceases by about age one, and thereafter children are more vulnerable to infectious diseases (Tanner 2005), so a focus on the toddler years allows us to assess the link between climate events in this potentially vulnerable group.

The dependent variable was the person's standing height, which we regressed on the following explanatory variables: (i) the mean annual level and the mean intra-annual monthly CV of rain during gestation, birth year, and ages 2–4, (ii) the mean annual level of temperature during gestation, birth year, and ages 2–4, (iii) the person's age and birth season, (iv) each parent's school attainment and ethnobotanical knowledge, (v) the height of the same-sex parent, (vi) a full set of dummy variables for surveyors ($n = 4 - 1 = 3$) and villages ($n = 13 - 1 = 12$), and (vii) a dummy variable for birth quinquennium. We next explain the methods used to collect data on the variables, how we constructed the variables, and the rationale for including the variables.

Variables

We measured the height of children, adolescents, and their parents (if parents were part of the panel study). We interviewed people $\geq$ age 16 (or younger if they headed a household) about their school attainment, age, and ethnobotanical knowledge, and we asked the main caretaker about the age and birth date of people $<$ age 16.

[a] Height. To measure standing height we followed the protocol of Lohman et al. (1988), used a portable stadiometer or a plastic tape measure, and recorded height to the nearest millimeter.

[b] Rain and temperature. We used the original climate data from San Borja. However, because two years (1995, 1996) had no rain data and other years had >1 missing values for monthly rain, for these missing observations of San Borja we imputed the predicted value of monthly rain using known monthly rain from three lowland towns near San Borja: Rurrenabaque, San Ignacio, and Trinidad, which lie 93 km, 101 km, and 194 km in a straight trajectory from San Borja.

Climate data from San Borja reflects accurately climate data in the villages of the sample. In studies among the Tsimane' that we did before the panel started, we measured daily rain and temperature (minimum, maximum, mean) during October 1999 to October 2000 in two villages: San Antonio and Yaranda. Among the villages of the panel, Yaranda and San Antonio are the most remote and one of the closest villages to San Borja. Yaranda and San Antonio lie 47.74 km and 10.34 km from San Borja in a straight trajectory. Two separate OLS regressions (not shown) of monthly rain levels in San Borja (dependent variables) on monthly rain levels in (i) San Antonio and (ii) Yaranda produced statistically significant positive coefficients ($p < 0.01$): San Antonio = 0.89, Yaranda = 0.52. Separate OLS regressions of monthly temperature in San Borja (dependent variable) on monthly temperature in the two villages also produced statistically significant ($p < 0.05$) positive coefficients for mean, minimum, and maximum temperature. The coefficients for temperature for San Antonio were: mean = 1.05, minimum = 1.47, maximum = 0.52. The coefficients for temperature for Yaranda were: mean = 0.76, minimum = 1.22, maximum = 0.34. We found no statistically significant difference at the $\geq$95% confidence level in rain or temperature variables between San Antonio, Yaranda, and San Borja, probably from their proximity to each other. For instance, mean monthly temperature in San Antonio, Yaranda, and San Borja were 26.57°C, 26.07°C, and 25.78°C.

The original rain data came aggregated by month but temperature data included several measures for a day. To harmonize the data set of temperature and rain, we estimated mean daily temperature and then computed monthly means from daily means.

We used data on monthly rain and monthly temperature to compute six measures for rain and six measures for temperature that refer to the calendar year. The appendix contains a description of how we created the 12 climate variables. Owing to multicollinearity, we could not use the three measures of mean intra-annual temperature variability (CV of temperature during gestation, birth year, and ages 2–4), so the regressions include only nine of the potential 12 climate variables.

[c] Age, birth season, and birth quinquennium. We used age or birth date to do the following: (i) assign people to age classes, (ii) estimate their birth season, (iii) estimate their birth quinquennium, and (iv) merge data about the individual with climate data.

The age variable allowed us to place people in the child or adolescent age class, and to estimate the gestation and birth years, and their toddler years. Because climate data was estimated for calendar years, we followed the following conventions when deciding on gestation or birth year: (i) for birth year a person was assigned to the year in which the person was born and (ii) for gestation year a person was assigned to their birth year minus one. As noted, we refer to age 1 as the period from birth to before the first birthday and we refer to ages 2–4 as the period from the first birthday (start of age 2) to the end of year four of life.

We used birth month to create a dummy variable for birth season (1 = person born during the coldest, driest months, May–July, inclusive; 0 = person born during warmer, rainy season, August–April, inclusive). Impetus to include a dummy variable for birth season comes from prior research among native Amazonians suggesting that seasonality is associated with food and energy availability and with physical activity (Rubin et al. 1986).

We used birth date (or age) to estimate birth quinquennium. The variable for birth quinquennium allows us to control for other events during the early life cycle unrelated to climate. For children (born 1993–2003, inclusive), we used one dummy variable that took the value of one if the child had been born 1995–1999 (inclusive), and zero if the child was born 1993–1995 or 2000–2003 (inclusive). For adolescents (born 1982–1992, inclusive), we used one dummy variable that took the value of one if the adolescent was born 1982–1986 (inclusive), and zero if the adolescent was born 1987–1992 (inclusive).

Last, we used birth date (or age) to merge the row of socio-economic, demographic, and anthropometric data of a person with climate date for that person. Although the procedure will produce accurate matches between true age and the date of climate events, it will also produce some mismatches because of how we estimated gestation and birth year. For instance, a person born in December 1999, would be assigned, correctly, 1999 as the year of birth but would be assigned 1998 as the year of gestation.

The age variable contained both random and systematic measurement error. About 80% of respondents guessed when reporting their age because they lacked birth certificates and did not know their exact age (Godoy et al. 2006). Surveyors added a code when respondents did not know their exact age or the age of their offspring. The code does not work well to separate people with accurate and inaccurate ages because respondents may have appeared to be certain of reported age when in fact they were not. Further, younger people may be more likely to have accurate measures of their age than older people because of increasing demand by government institutions (e.g. schools) to report age. Random measurement error in age plus systematic age-dependent measurement error would both work in the same

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[d] Parental school attainment, ethnobotanical knowledge, and height. Parental attributes affect child nutritional status and also could mediate the association between climate variables and offspring height. Among parental attributes we measured the following: (i) two forms of human capital – school attainment and ethnobotanical knowledge – that might be associated with own and offspring health (Godoy et al. 2005a; McDade et al. 2007) and (ii) the height of the same-sex parent.

We asked parents about the maximum school graded they had completed and coded answers so they matched the grade completed (e.g. 3 = completed third grade). To measure ethnobotanical knowledge we collected similarity judgments using a multiple-choice test of 15 plants selected at random from a list of 92 plants developed in an earlier study (Reyes-García 2001). In the test we asked people whether they could use the plants for food or medicine. We used cultural consensus analysis (Romney et al. 1986; McDade et al. 2007) to calculate the most common response among people $\geq$ age 55, and used the latter to calculate scores of ethnobotanical knowledge for each parent (Reyes-García et al. 2003, 2005). We include the height of the same-sex parent to control for heredity, an important determinant of height (Henneberg and van den Berg 1990).

[e] Other. Dummy variables for surveyors and villages were included to control for the confounding role of different surveyors and for fixed attributes of the village. Some fixed attributes of the village, such as abundance of natural resources and proximity to town, might bear an association with height and climate.

Analysis

For the statistical analysis we used STATA for Windows, version 10 (StataCorp, College Station, TX, USA). To estimate climate trends, we used OLS regressions with the natural logarithm of annual temperature or rain (dependent variables) against a year variable (explanatory variable). We tested and corrected regressions for heteroskedasticity and for serial correlation.

To ease the interpretation of results, we took natural logarithms of height (dependent variable) and the following explanatory variables: (1) CV of temperature and rain during gestation, birth year, and ages 2–4, (2) parental ethnobotanical knowledge, and (3) the height of the same-sex parent. For brevity and since the article focuses on the association between climate and height, we only report and discuss the coefficient of climate variables.

Results

Secular trends of rain and temperature

Figure 2 shows total annual rain and intra-annual monthly CV of rain (1943–2005) and Figure 3 shows mean annual temperature and intra-annual monthly CV of temperature (1973–2005). The two figures show that this area of Bolivia has experienced the following: (i) an increase in the level and variability of temperature, (ii) a decline in the

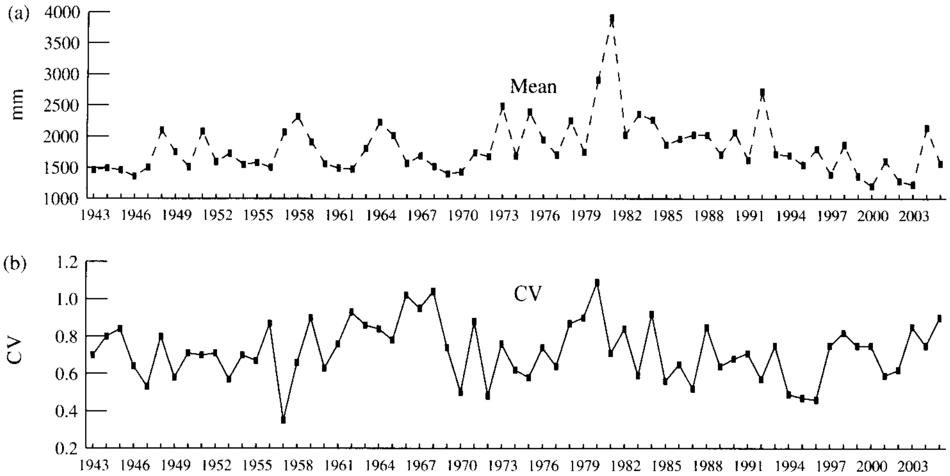

Figure 2. Total annual rain (mm) and intra-annual monthly coefficient of variation (CV = standard deviation/mean) of rain, 1943–2005, for San Borja airport, department of Beni, Bolivia.

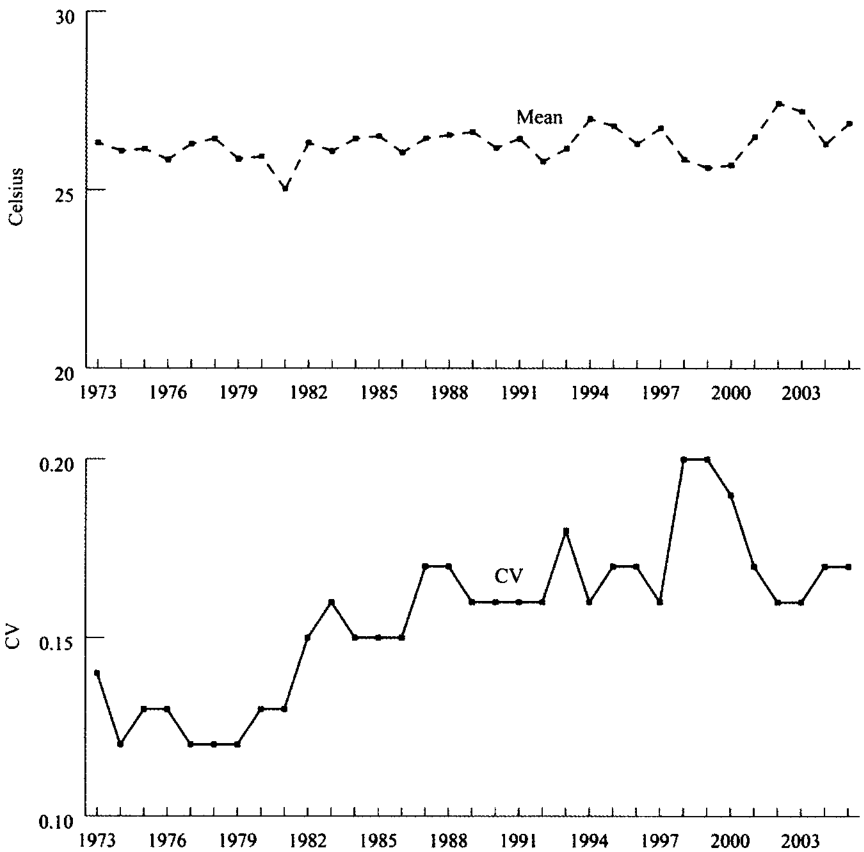

Figure 3. Mean annual temperature (Celsius) and intra-annual monthly coefficient of variation (CV = standard deviation/mean) of temperature, 1973–2005, for San Borja airport, department of Beni, Bolivia.

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level of rain, and (iii) more variability in rain. During 1973–2005, mean annual temperature and the intra-annual monthly CV of temperature Δ by +0.06% ($p<0.11$) and +0.54% each year ($p<0.08$). During 1943–2005, mean annual rain and the intra-annual monthly CV of rain Δ by −0.11% ($p<0.68$) and +0.03% each year ($p<0.81$). The figures suggest no statistically significant secular change in climate at the conventional 95% confidence level.

Pearson correlation coefficients between the four main climate variables (annual level and CV of rain and temperature) using the Šidák method to adjust significance levels for multiple comparisons produced no statistically significant results at the ≥95% confidence level, with two exceptions. The mean annual level of rain was negatively associated with the mean annual level of temperature (correlation = −0.53, $p<0.006$) and with the intra-annual monthly CV of temperature (correlation = −0.46, $p<0.04$).

Height of children and adolescents

Table I shows two noteworthy findings. First, climate events during gestation, birth year, and ages 2–4 bore no statistically significant association at the ≥95% confidence level with the height of adolescent girls (column [C]) or adolescent boys (column [D]) or with the height of girls 2–12 years of age (column [A]). Second, climate events during gestation, birth year, and ages 2–4 were positively associated with the height of boys 2–12 years of age (column [B]).

The coefficients of column [B] imply the following about boys 2–12 years of age. First, an increase of one standard deviation in rain during a boy's birth year was associated with a 6.68% ($p<0.01$) increase in height (~5.76 cm). Second, a 1% increase in the intra-annual monthly CV of rain during a boy's birth year was associated with a 0.49% ($p<0.03$) increase in height (~0.43 cm). Third, a 1% increase in the intra-annual monthly CV of rain while the boy was 2–4 years of age was associated with a 1.40% ($p<0.02$) increase in height (~1.38 cm). Fourth, an increase of one standard deviation in mean annual temperature while the boy was 2–4 years of age was associated with a 19.85% ($p<0.03$) increase in height (~17.10 cm).

Tests of joint statistical significance for the climate variables of column [B] suggests that among boys 2–12 years of age, climate events during birth year ($F_{3,234}=2.65$, $p<0.04$) and climate events while boys were 2–4 years of age ($F_{3,234}=2.82$, $p<0.03$) bore a stronger association with height than climate events during gestation ($F_{3,234}=1.73$, $p<0.16$). A boy's height bore a stronger association with the mean annual level of rain ($F_{3,234}=2.22$, $p<0.08$) than with the intra-annual monthly CV of rain ($F_{3,234}=1.73$, $p<0.16$) or than with the mean annual level of temperature ($F_{3,234}=1.61$, $p<0.18$).

The coefficients of column [B] are large compared with other known variables that influence height. For example, the coefficients of rows I.B.1–2 imply that a 1% increase in the coefficient of variation during birth year or years 2–4 of life are associated with an increase in height of 0.49% and 1.40%. In contrast, an additional year of mother's schooling was associated with only 0.16% taller height ($p=0.54$) and a 1% increase in the height of a boy's mother or father was associated with 0.20% (mother; $p=0.22$) and 0.17% (father, $p=0.13$) taller stature. These figures suggest that climate variables, when they are statistically significant, also produce large, meaningful biological associations.

Table I. Results of OLS multiple regressions of (a) dependent variable = standing height (in natural logarithms) of Tsimane' children and adolescents in 2005 and (b) explanatory variables = level and coefficient of variation (CV) of rain and temperature during the early life of children and adolescents, plus controls.

	Age in years (inclusive) of person			
	2–12 (children)		13–23 (adolescents)	
Explanatory climate variables	♀ [A]	♂ [B]	♀ [C]	♂ [D]
I. Rain during person's early life:				
A. z score of mean annual level of rain in:				
[1] Year of gestation (age 0)	−0.006	0.002	−0.06	0.07
[2] Year of birth (age 1)	0.03	0.06*	0.28	−0.28
[3] Years 2–4 (mean z score during ages 2–4)	0.01	−0.04	0.59	−0.52
B. Natural log of annual CV of monthly rain in:				
[1] Year of gestation (age 0)	0.11	0.29	0.04	−0.18
[2] Year of birth (age 1)	0.23	0.49*	0.43	−0.51
[3] Years 2–4 (mean annual CV during ages 2–4)	0.57	1.40*	1.89	−1.68
II. Temperature during person's early life:				
A. z score of mean annual temperature in:				
[1] Year of gestation (age 0)	−0.01	−0.0003	−0.06	0.09
[2] Year of birth (age 1)	0.01	0.04	0.32	−0.28
[3] Years 2–4 (mean z score during ages 2–4)	0.09	0.19*	0.40	−0.36
Constant	2.99**	2.70**	4.11	−3.58
Observations	257	268	104	114
R^2	0.88	0.88	0.51	0.69

Notes: * and ** are statistically significant coefficients at ≤5% and ≤1%, respectively. Controls not shown include (a) school attainment and ethnobotanical knowledge of each parent, (b) standing height of same-sex parent, (c) person's age and birth season, and (d) dummy variables for (i) villages, (ii) surveyors, and (iii) birth quinquennium. Regressions include robust standard errors.

Robustness analysis of height for boys 2–12 years of age

Table II contains a summary of further analysis to ensure the robustness of the main results shown in column [B] of Table I. The regressions of Table II are identical to the regression of column [B], Table I, except for the changes described in the notes to Table II. Changes introduced in Table II include other definitions of temperature (e.g. minimum or maximum rather than mean), controlling for the non-independence of siblings through a household fixed-effect model and clustering by households, other ways of expressing z scores of mean temperature and rain, and restricting the analysis to offspring whose caretaker reported being certain of the offspring's age. For ease of comparison, the row called 'Base, Table I' contains the coefficients of the climate variables from column [B], Table I.

The results of the sensitivity analysis support the main conclusions of Table I. Of the four statistically significant coefficients of column [B], Table I, three of them – (i) the mean intra-annual monthly CV of rain during birth year and (ii) during ages 2–4 and (iii) the z score of mean annual temperature during ages 2–4 – retained their sign and remained statistically significant.

Table II. Results of sensitivity analysis for column [B], Table I.

Coefficients from baseline	Rain						Temperature		
	Level (z score) at age:			Log CV at age:			Level (z score) at age:		
	0	1	2–4	0	1	2–4	0	1	2–4
Regressions; Table I	0.002	0.06*	−0.04	0.29	0.49*	1.40*	−0.0003	0.04	0.19*
Changes to baseline regressions of Table I									
1	−0.02	−0.003	0.02	−0.02	−0.003	0.97*	−0.001	0.01	0.17*
2	−0.02	0.05	−0.04	−0.05	0.24*	0.58*	0.02	0.09	0.32*
3	0.0002	0.06*	−0.04	0.29	0.49*	1.40*	−0.0003	0.04	0.19*
4	−0.05*	−0.18	−0.09	0.70*	0.72*	0.45	0.07	0.02	0.21*
5	−0.05	−0.18	−0.09	0.70*	0.72	0.45	0.07	0.02	0.21*
6	−0.23*	0.13*	†	−0.29	0.47	†	−0.17*	0.02	0.16
7	−0.004	0.06*	−0.04	0.30*	0.52*	1.43*	0.00002	0.04*	0.20*

Notes: Same notes as in Table I. †Variable dropped owing to multicollinearity.
Notes below describe the changes made to the baseline regression; numbers below correspond to numbers in the first column of Table II:
[1] Minimum rather than mean temperature for z score of temperature.
[2] Maximum rather than mean temperature for z score of temperature.
[3] Household fixed effect with clustering by household; clustering introduced to control for the non-independence of siblings.
[4] z score of the logarithm of rain and the logarithm of temperature.
[5] Original regressions with changes in [3] and [4] introduced simultaneously.
[6] Limited to children $\geq$4 to have complete temperature and rain data for three lead years (ages 2–4) or years 2–4 after birth. (year 1). These people would have been born 1982–2001 (rather than 1982–2003) and would have been 4–23 years of age at the time of the survey (2005).
[7] Limited to children whose caretaker reported being certain of the offspring's age.

Limitations and strengths

Besides some of the limitations already noted (e.g. measurement error with age), here we discuss two other limitations. First, we only had data on age and birth season to include as covariates for the person, but other attributes of the person (e.g. illness) contribute to height. Among Tsimane', as among other native Amazonian populations, child growth stunting is common (Foster et al. 2005), probably from parasitic infections and poor dietary quality (Tanner 2005; Gurven et al. 2007). We had objective indicators of health (e.g. parasite load, C-reactive protein) for earlier surveys but not for the 2005 survey so we could not include objective measures of health in our analysis. Our inability to control for the person's stock of past physical health likely biases our parameter estimates for climate variables in an unknown size and direction. Second, we had a small sample size of observations for adolescent females ($n = 104$) and males ($n = 114$). The weak statistical results for this age class might reflect the small sample size used, particularly if the magnitude of the true effect is small.

On the positive side, our study highlights the usefulness of the following: (i) separating the level from the variability of climate variables – and including them both – when assessing the association between health and climate, (ii) identifying the stage in the life cycle when people might be most vulnerable to climate events, (iii) identifying the groups most likely to be vulnerable to climate events, and (iv) estimating the simultaneous effects of different climate variables on health.

Discussion and conclusions

We organize the discussion around the following topics: (i) hypotheses, (ii) links to other studies, (iii) secular changes in climate and height, and (iv) directions for future research.

Hypotheses

Hypothesis 1. Results lend partial support to hypothesis 1 that levels of temperature or rain bear a positive association with height. In most cases, the level of rain or temperature bore no statistically significant association with height, but when in did, as among boys ages 2–12, it bore the correct, positive sign predicted by hypothesis 1.

Hypothesis 2. We found no support for hypothesis 2 that mean intra-annual variability in climate variables bore a negative association with height. In fact, nine of the 12 coefficients of section IB, Table I, were positive. Note that the parameter estimates for the CV of rain were all positive for boys 2–12 years old, but all negative for males ages 13–23. If we pool the two age classes for boys and re-estimate the regression of column [B] for males ages 2–23 (regressions not shown), then we get the negative coefficients predicted by hypothesis 2 for the CV of rain during gestation (-0.07; $p<0.001$), birth year (-0.19, $p<0.001$), and ages 2–4 (-0.35, $p<0.001$). If we pool the two age classes for girls we also obtain negative coefficients for the CV of rain during gestation (coefficient $=-0.12$, $p<0.01$), birth year (coefficient $=-0.19$, $p<0.01$), and ages 2–4 (coefficient $=-0.51$, $p<0.01$). These regression results suggest that hypotheses 2 hinges on how one treats age classes; an analysis with pooled results produces the expected negative associations between the CV of rain and height, but an analysis done separately for children and adolescents, as done here, produces no support for hypothesis 2.

We believe that of the two approaches – separate age classes and pooled age classes – the approach presented in Table I with separate age classes is more reliable for biological and statistical reasons. On the biological side, children and adolescents have different growth trajectories and energy requirements, so climate perturbations should affect each age class differently. On the more technical side, the results of tests for interaction effects showed that climate variables indeed had differential effects on height by age classes.

Hypothesis 3. The results of tests of joint statistical significance for boys supports hypothesis 3 that climate events during gestation and birth year bore weaker associations with height than climate events during ages 2–4. Support for hypothesis 3 is partial because even among boys 2–12 years of age, climate variables during birth year bore a statistically significant association with height ($F_{3,234}=2.65$, $p<0.04$). Note that the coefficients of climate variables for birth year for boys in column [B], Table I, are at least twice as large as the size of the coefficients for girls (column [A]). We expected breastfeeding during the first year of life to have inoculated boys from climate events that took place during their first year of life, but apparently it did not.

We have no convincing explanation for why boys 2–12 years of age might be more susceptible to climate events (particularly during birth year) than girls of the same age. The finding is surprising because in earlier studies we found no evidence of girl–boy disparity in anthropometric indicators, nor did we find evidence of parental preferences for children of one sex over the other (Godoy et al. 2007b). The findings of Table I suggest that the bias works in favor of boys; greater levels of rain or greater variability of rain during birth year were associated with greater height of boys relative to girls. One possibility might have to do with differences in the length and quality of breast feeding between girls and boys. We have no data on the topic, but it is possible that young mothers have started breastfeeding boys slightly longer (or perhaps more frequently) than girls, and perhaps giving boys more nutritious food supplements than girls. Unfortunately, we lack intra-household data to settle the issue. A second possibility has to do with greater measurement error in the age variable for girls than for boys, which would produce a greater attenuation bias in the coefficients for girls than boys. Though theoretically possible, in our ethnographic work we have not detected greater accuracy when reporting the age or birth date of boys over girls.

A third explanation has to do with female resilience based on genetics. Across various vertebrate taxa it has been shown that helminthes, an important source of infection for the Tsimane' (Tanner 2005), tend to infect males more than females (Muehlenbein and Bribiescas 2005). Similarly, Japanese macaque (*Macaca fuscata*) males have increased infectious disease mortality than females (Muehlenbein and Bribiescas 2005), and evidence in humans suggest that male mortality from internal causes exceeds female mortality at all ages (Kruger and Nesse 2004). Since young females might be more resilient than young males, climate perturbations would harm male height more than female height. The problem with this explanation is that, if true, then we should have found climate events early in life having weaker effects on adult height among females than among males, but in our earlier study (Godoy et al. 2007a) we found the opposite: climate events early in life depressed female not male adult height. Also, genetic-based explanations would not unravel the anomaly of why climate events among pre-adults produce positive effects only among males.

Hypothesis 4. We found no support for hypothesis 4 that climate variables bore a stronger association with the height of females than males. In fact, we found no statistically significant association at $\geq$ 95% confidence level between climate variables and the height of females and we found that climate tended to affect only the height of boys. Under hypothesis 3 we already discussed why this might be so.

Recall that in an earlier study (Godoy et al. 2007a) we found that climate events during the early life cycle were negatively associated with the height of females, so one would have expected climate variables to also depress the height of females before they reached adulthood. We offer two explanations (one technical and one substantive) for the discrepancy between the earlier and the later study.

The first, technical, explanation has to do with the method of analysis. As noted, if we pool the two age classes or if we pool the two age classes and both sexes (and include a dummy variable for a person's sex), then we find strong associations between many climate variables and height, and many of the associations would be consistent with the results we found among adults. So one explanation for the discrepancy has to do with how one decides to treat age classes and sex in the statistical analysis. For reasons already discussed, the analysis disaggregated by age class and sex, as done here, yields more reliable estimates.

The second, substantive, explanation has to do with changes in the experience between younger and older cohorts, between those born before the 1980s and those born after the 1980s. Adult women or those born before 1980 might have been poorly protected against climate perturbations and this would explain why we found negative associations between climate events early in their life and their adult height. Improvements in health care during the last two decades (Gurven et al. 2007) may provide better protection against climate perturbation for the younger females of this study, weakening the associations between climate events early in their life and their height as children and adolescents.

Links to other studies

We know of only one study that has examined the association between climate events early in life and pre-adult height. Alderman et al. (2006) found that children in Zimbabwe 12–36 months of age affected by the droughts of 1982–1984 attained 0.72 lower *z* scores of height-for-age by the time they reached age 17–18. The droughts had the same effect on the height of girls and boys. Unlike us, Alderman et al. focused only on rain, on adverse weather shock, on the level rather than on the variability of rain, and on very young children at the time of the event.

Our finding that climate events early in life bear a weak association with the height of children and adolescents supports prior studies with Tsimane' children and young adults suggesting that their short-run nutritional status is shielded from many idiosyncratic adverse shocks, such as illness, theft, and crop loss suffered by the person or the household (Godoy et al. 2007b). Protection comes from traditional systems of sharing within and across villages, economic diversification, and from reliance on hardy perennials and tubers ideally suited to weather lean spells.

Secular change in climate and secular change in height

We found no statistically significant secular change in rain (1943–2005) or temperature (1973–2005), a result that meshes with the absence of a secular trend in adult height among Tsimane' born during 1920–1980 (Godoy et al. 2006). The absence of a visible link between secular changes in climate and height among Tsimane' could reflect the offsetting role of difference forces. For example, warmer temperatures might contribute to taller stature, but warmer temperatures might also produce changes in the amount and composition of foods consumed, which might depress height. If so, then secular changes in temperature would produce countervailing forces and no visible secular change in height. The absence of a link between secular change in climate and secular change in height could also reflect the time span chosen for the analysis. Perhaps secular changes in climate have to operate over a broader time span before one can detect secular changes in height. An analysis confined to only a few decades, as done here, might not provide enough resolution to detect secular changes in height.

Directions for future research

The increasing interest in global warming has paralleled the increasing number of public-use local data sets on daily weather events extending far back in time. The confluence provides an ideal opportunity to examine a wide range of new topics in human biology. We can exploit the data sets to estimate how weather events during the early life cycle affect health later in life, as done here. If one examines the topic in poor rural societies of developing nations, then one should be able to assess whether much that has been written about the dominant role of early life events on health throughout the life course in industrial societies also applies to pre-industrial societies. The topic allows one to assess the vulnerability of poor rural people. More importantly, the coupling of cross-sectional data about people with time-series data on local climate should allow one to examine trans-generational effects of weather events. It is possible that in poor rural settings of developing nations, weather events leave a health imprint not only on the person who directly experiences the event, but also on their offspring. Our data set was too limited to explore these links, but other researchers with

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larger samples and longer time-series records of climate events might be able to pursue this promising new line of research.

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Declaration of interest: The authors report no conflicts of interest. The authors alone are responsible for the content and writing of the paper.

Note

1. Rain data was purchased from the Administración de Aeropuertos y Servicios Auxiliares a la Navegación Aérea (AASANA); postal address: Calle Reyes Ortiz esquina Federico Suazo No. 74, Edificio FEDEPETROL 6°–14° Pisos, Casilla No 4382, La Paz, Bolivia; telephone: 591 2351 341, 591 2343 112; fax: 591 2342 731. We downloaded temperature data on February 2007, from the web site of the National Oceanic and Atmospheric Administration (NOAA), USA Department of Commerce (http://www.ncdc.noaa.gov/oa/ncdc.html); postal address: NOAA, National Climatic Data Center, Federal Building, 151 Patton Avenue, Asheville NC 28801-5001, USA; telephone: 828-271-4800; fax: 828-271-4876; E-mail: ncdc.info@noaa.gov.

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