Climate effects and stature since 1800

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Abstract: During the last 30 years, economic and social historians have collected and analysed large amounts of anthropometric data in order to explore key aspects of the human past. Attention has also been devoted to the examination of factors that can exert an influence on stature. This article outlines the different ways in which climate might influence stature, either directly or indirectly. It then uses Geographical Information System (GIS) software to explore the relationship between variations in temperature and precipitation and the average heights of men in France, India, Mexico, Spain and the United States (US) over the last two centuries. It is possible to observe an influence of climate on stature in some countries, especially during the nineteenth century, but the relationship weakens across time and largely disappears in recent decades. The attenuation of this relationship is attributed to a process of "technophysio evolution" as countries modernised and developed economically.

Keywords: Climate, Weather, Health, Height, Anthropometry

Version: 10 February 2018.

1. Introduction

The world's climate is of interest to historians and economists because environmental conditions affect the health and development of the entire population. According to the Intergovernmental Panel on Climate Change (IPCC), "Weather and climate have a profound influence on life on Earth. They are part of the daily experience of human beings and are essential for health, food production and wellbeing" (IPCC 2001, 87).[1] However, it has often proved difficult to establish a clear connection between climate and measures of health and wellbeing. One reason for this has been a shortage of adequate meteorological data. Another is that climate is related to health through multiple complex pathways. A third is the difficulty of choosing a suitable measure of wellbeing which can be applied to different countries over long periods of time.

One solution to the third challenge is that adopted by anthropometric historians who use height and weight to investigate the health and wellbeing of earlier generations (Floud et al. 2011). Height is a cumulative measure of conditions affecting the life of the individual throughout the growth period, and is affected by the quality and quantity of an individual's diet and the demands placed on the body's resources by exposure to disease and the use of energy for play and work. Genes are very important at the individual level; however, nutritional and environmental conditions from conception to maturity determine how far genetic potential is realised during development. During the last two decades, anthropometric historians have become increasingly interested in the relationship between height and a wide range of social, economic and environmental factors such as disease, inequality, urbanisation and food prices, but the extent to which meteorological factors may have influenced height has not been examined in as much detail.

One of the main challenges associated with the use of meteorological data is their inherent seasonality. Because meteorological variables display large short-period volatility, scholars have smoothed the data using moving averages or other filters. Although these techniques help to ensure that long-term fluctuations are highlighted, they can also obscure the impact of seasonal variability, which can be vital for agricultural production. A second problem is the absence of data for specific geographical areas. For example, when Baten (2001) examined the relationship between temperature and height in eighteenth-century Bavaria, he used information on winter temperatures in Switzerland. Similarly, when Komlos (2003: 180-3) undertook his investigation into the determinants of height in seventeenth and early eighteenth century France, he used climatic data from Paris, England and Switzerland.

These problems increase the further back in time one travels. Steckel and Rose (2002) incorporated height measurements into a health index and then compared variations in the value of this index with a range of factors, including settlement size, topography and climate.[2] Due to the absence of more precise data, they categorised climates as being either tropical, sub-tropical or temperate. They were somewhat surprised to conclude that the "climatic distinctions were irrelevant for the health index", and they suggested that "this might be the result of insufficient diversity in our sample and/or poor measures of climate" (Steckel and Rose 2002: 567-87).

Despite these difficulties, a number of scholars have found evidence of a relationship between climatic variables and stature in different parts of the world over the last three centuries. Baten (2001) concluded that warm winters had a positive effect on the heights of

men who grew up in Bavaria during the eighteenth century because farmers were able to increase the production of grains and protein sources. Komlos et al. (2003) argued that increasing temperatures led directly to increases in stature in France because people needed fewer calories to keep warm; in addition lower levels of summer and autumn rainfall had an indirect effect through increased food production. More recently, Moradi (2012) showed that female heights were positively associated with increased temperatures in sub-Saharan Africa. In Mexico, Challú (2009) found that drought and El Niño events had a negative impact on the heights of people growing up between 1730 and 1830, because of reduced access to food; Agüero (2014) reported a similar relationship during the second half of the twentieth century (although Grajales-Porras and López-Alonso (2011) found that the Mexican drought of 1785-1786 did not cause a decline in heights).

This illustrates an important point: even if there is a relationship between climate and stature, one would not necessarily expect it to be consistent within or between countries, or over time. For example, one might expect similar variations in either temperature or rainfall to have a somewhat larger effect in countries with more equable climates than in countries where the normal range of meteorological variations is greater. It is also important to recognise that our ability to moderate the impact of climatic variations on stature has increased dramatically over the last three hundred years. Fogel and Costa (1997, 49) argued that through the process of "technophysio evolution"—the synergism between rapid technological change and the improvement in human physiology—increasing human control over the environment has weakened the relationship between natural factors, such as climate, and height.

In this paper we "map" changes in the relationship between temperature and precipitation and average male stature over the last 200 years through a multi-country study using modern climatic data reconstructions. We attempt to look at variations in temperature and precipitation within cohorts and discuss how the sensitivity to these variations changed over time with a technique known as rolling regression. Our main aim is to explore the relationship between variations in climate and precipitation and stature, and to examine the extent to which this relationship changed over time. We use an analysis of five countries to illustrate the kinds of responses we can observe.

In the next section, we outline the different ways in which climate might influence stature using a conceptual framework. In sections 3-5 we describe our height data for men born in France, India, Spain, Mexico and the United States (US) since 1800 and climatic data and show how we matched individuals with its climatic correlates through the aid of Geographical Information Systems (GIS) software. In sections 6-7 we examine the extent to which the relationship between stature and climate has changed over time within birth cohorts of each of the five countries and section 8 concludes.

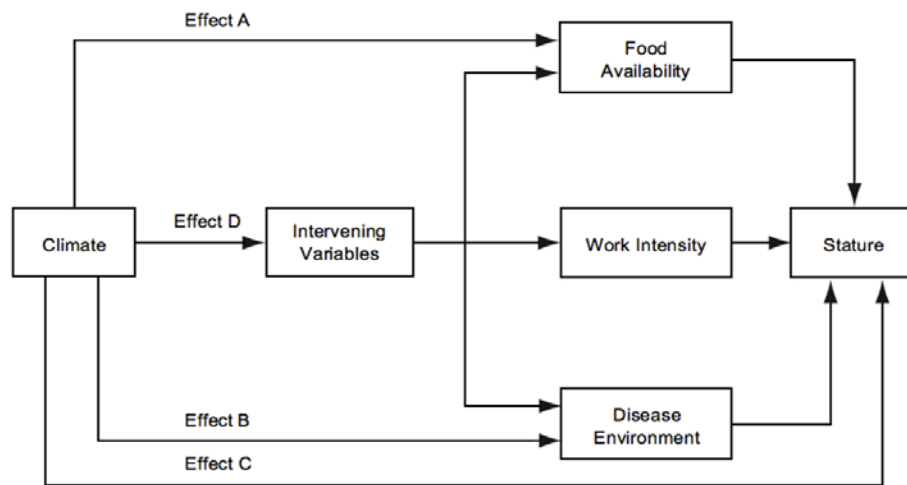## 2. Conceptual framework

In Figure 1 we depict the four ways in which climate might influence stature through (A) its direct effect on food availability, (B) its direct effect on the disease environment, (C) its influence on the number of calories needed to maintain physiological functioning under different climatic conditions and through the effect of exposure to sunlight on the synthesis of

Vitamin D, and (D) its indirect effect on food availability, the disease environment and work intensity.

The originality of this conceptual framework lies in the way these effects are conceptualized and not in the sole identification of the effects. For instance, Komlos (2004) already recognised that climate could affect stature through food supply and Dell et al. (2014) surveyed the impact of climate on agricultural output, industrial output, labour productivity, energy demand, health, conflict, and economic growth. Our aim is to summarize and integrate the relationship between climate and height into one comprehensive picture.

Figure 1: Conceptual framework

Effect (A) is based on previous anthropometric literature which suggests a relationship between climate and stature through agricultural production (Komlos 2003). Food is the most basic need and changes in food availability can be closely related to changes in height and mortality (Harris et al. 2015, 113). Agriculture is the main source of calories for human consumption, and variations in weather and climate, which can have a direct impact on plant systems and the production of staple foods, could favour arable over pastoral farming or *vice versa* (Ingram et al. 1981). For instance, climate can affect the choice of crops and level of pastoralism, thereby speeding the pace of land degradation and desertification and limiting the sources of protein intake (Food and Agriculture Organisation 1995). However, technological change such as the kind of agriculture practised, social customs such as those affecting diet, and the allocation of food within families, also appear to be important when considering the relationship between climate and stature through nutrient intake.

Effect (B) reflects the idea that climate can affect stature through its influence over the disease environment. It can affect the spread of vector-borne diseases such as diarrhoea, cholera and malaria (Small et al. 2003). Malaria, which nowadays accounts yearly for more than one million deaths worldwide, weakens the immune system and raises susceptibility to other diseases such as anaemia, and respiratory and rheumatism/musculoskeletal diseases (Hong 2011). Martínez-Carrión (1994) found that in Murcia (Spain) between the 1840s and the 1900s the shortest recruits were born in the countryside where malaria was more endemic. Hong

(2011) reported that Union Army veterans who spent their childhoods in the most malarial counties of the US were about 2.8 cm (1.1 in) shorter at enlistment than those who grew up in the least malarial county. Periods of abundant rainfall can also cause flooding, creating conditions ideal for the transmission of water-borne diseases and food-borne infections, inhibiting the proper digestion and absorption of nutrients (Vörösmarty et al. 2000). Some important interactions take place between climate-related diseases and nutrition. Lloyd et al. (2007) estimated that higher rainfall levels increased the incidence of infant diarrhoea through contamination of water resources and reduced hygienic practices. Protein absorption is reduced by 10-30% (and sometimes by as much as 40%) in children with diarrhoea (Scrimshaw and SanGiovanni 1997). Checkley et al. (2008) calculated that about 25% of stunting among infants in developing countries can be attributed to having experienced five or more episodes of diarrhoea before the age of two years.

Effect (C) is the direct impact of climate on stature insofar as the body needs to expend higher amounts of energy to maintain its optimal temperature during cold winters and hot summers (Bogin 1999). This is part of the body's thermoregulatory process with heat dissipation in hot environments to avoid hyperthermic stress and heat retention in cold environments to avoid hypothermia. However, the potential magnitude of this effect remains under discussion. Sharpe (2012: 1485) argued that "in cold weather energy is preferentially used to generate heat rather than for growth", but Kelly and Ó Gráda (2013: 1156) claimed that the calorific needs associated with colder temperatures might not be so great and Meredith and Oxley (2014) suggested that they were unknown. It has also been observed that sunlight has a strong effect on the growth rates of children (Bogin 1999). Between 90-95% of our Vitamin D comes from direct sunlight exposure (Holick 2004). Sharpe (2012) highlighted the effect of insufficient sunlight as a cause of rickets. She argued that nineteenth century British children were stunted because the effects of urban pollution denied them access to sunlight.

Finally, effect (D) identifies some of the ways in which climate can influence other factors which may themselves affect stature. For example, in very cold or very hot environments, both mental and physical working capacity can be reduced. If this affects earnings, the threat of poverty may be increased. This may also lead to greater demand for child labour, forcing more children into work. Labour market participation could increase children's need for calories, even though it might also increase their entitlement to calories and therefore improve rather than detract from their basic welfare (Humphries 2010). A change in climate or weather can also damage infrastructure and transport networks, thus hampering trade, which might lead to regional food shortages. If resources are depleted, this can lead to population movements and/or conflicts over the distribution of scarce resources (Parker 2013). Climatic conditions may have imposed limits on the scope of urbanisation in the past and encouraged urbanisation if they made rural conditions unsustainable. Effect (D) may also confound the relationship between climate and stature insofar as changes in the relationship between height and climate may reflect geographical changes in the distribution of wealth, which are themselves associated with climatic variables. For example, if wealthier people migrate to warmer regions, their children will be taller, but the height of the children might reflect the wealth of the parents more than the warmth of the climate.

3. Selection of the countries

For the comparative study of the relationship between meteorological conditions and stature encompassing the last 200 years, we have assembled individual male height data for a range of countries based on a collection of data from previously published studies.[3] From the countries with enough data to cover most of the last 200 years, we concentrated on sources that were expected to offer the most consistent samples of the underlying population over time. We avoided data from slave records in Africa or the US and convict samples from Europe, Latin America and the US.[4] Our analysis is confined to males because most of the historical sources only reported the height of adult male populations. We identified studies which appeared to cover a relatively long period of time (100-200 years). We contacted the authors of these papers and some of them agreed to share their data with us. Eventually we were able to gather data from 11 countries. However, in this paper we focus only on five: France, India, Mexico, Spain and the United States.[5] These five countries were selected because they provide good quality data over an extended period of time and cover a range of different climatic conditions and economic experiences. In two countries (France and Spain) our collection of data for one source was long enough to cover the last 150-200 years while, in the other three, we pooled data from different sources. In some cases we gained access to data for one period (for example 1800-1875) but not for a subsequent period (for example 1875-1950). We also discarded some data because place of birth, a key variable in our study, was not recorded consistently.

Table 1 summarises key features of the five countries and Figure A1 of the Appendix illustrates the main geographical patterns. The climate of France has been one of generally cool winters and mild summers with year-round rainfall for the most part, but of mild winters and hot summers in the south. The mean temperature between 1800 and 1999 was 12.4ºC with a rise of 1.1ºC over the course of the period. Our height data come mainly from central France and Alsace-Lorraine in the east (though we do have some data from all parts of the country). The average temperatures and rainfall reported in Table 1 therefore probably reflect the experience of our sample fairly well.[6] There was an upward trend in temperature form the 1880s onwards, with a rapid warming after the 1970s. Most of France receives a moderate amount of precipitation throughout the year, although regional variations exist within France: 670 mm in Paris, 800 mm in Lyon, 980 mm in Bordeaux and 1,140 mm in Brest, with rainfall being greater near the high mountains. The mean annual rainfall since 1800 has been 818.2 mm, with levels decreasing during the second half of the nineteenth century and relatively narrow fluctuations during the twentieth century.

Spain's climate is characterised by cold winters, hot summers and low and irregular rainfall. Our height data are concentrated in the Spanish Mediterranean Levant (Murcia and Valencia), which is characterised by very mild winters and long warm to hot summers, though we have some data from most areas of Spain apart from the northern and north-western littoral (see Appendix A1). Average temperature and rainfall from 1800-1999 were 17.2ºC and 364.8 mm in the Mediterranean area (13.5ºC and 607.3 mm in Spain as a whole). Similar to France, over the period 1800-1999 mean temperatures in Spain rose by about 1ºC, despite falls during the 1810s, 1880s and 1970s. Low levels of rainfall were observed in the 1900s, 1920s and after 1980 with a more significant downward trend when compared to France.

Mexico's climate varies from semi-arid in the north to sub-humid in the south (Endfield 2008: 29). Our height data for the nineteenth and early twentieth centuries come mainly from

military records for the *Bajío* region, supplemented by a smaller proportion of passport holders from urban areas. For the second half of the twentieth century we use a nationally representative survey. The *Bajío* region lies towards the middle of this climatic gradient with a moderately arid climate. We believe, therefore, that the national-level climate series probably reflect the experiences of this region reasonably well. We do not have data for the first half of the nineteenth century but the mean temperature in Mexico since the 1850s was 20.6ºC with a rise of 0.9ºC by 2000. Mean rainfall since 1901 was 732.7 mm, and also shows an upward trend with decades of abundant rain such as the 1930s and 1960s. However, rainfall is particularly low in the north-west coastal zone and regions such as Tijuana receive less than 250 mm per year.

Even though the bulk of India has a tropical climate, its climate is influenced by the Himalayas and the Thar Desert, and the wide variety of terrain leads to a wide variety of climatic conditions. Agriculture and life in most of India is highly dependent on the *kharif* (the country's monsoon wet-season crop), cultivated from June to September during which period around 90% of India's rain falls. The country can be divided roughly into seven climatic regions: the northern mountains with the Himalayas and their foothills; the northern plains, a low-lying region from Punjab to the Ganges delta with a humid subtropical climate; the Rajasthan Desert, being one of the warmest places in India with low rainfall; the Deccan plateau in central India, ranging from a semi-arid climate in the north to tropical in the rest of the region; the west coast, where rainfall is abundant during the monsoon season and heat can be very oppressive because of the humidity; the south-east coastlands, which are also exposed to monsoon rains with a rise in temperature and humidity; and Assam in the extreme north-east, being a region of mountains with a similar climate to that of the northern plains. While the data collected from the twentieth century cover large parts of northern, western and eastern India, our nineteenth century data are mostly from Uttar Pradesh and surrounding states in the northern plains, but we also have some data from southern states, as the geographical composition of the sample changed over time (Brennan et al. 1997, 190-1).[7] The average temperature in India between 1813 and 1999 was 23.9ºC (with a rise of 0.9ºC across that period) while temperatures in Uttar Pradesh also showed an upward trend increasing from 24ºC in 1850 to 25.5ºC in 2010. With an average rainfall level of 1,121.5 mm each year, the levels of rain rose during the second half of the nineteenth century, fell at the start of the twentieth century and then fluctuated more widely until the 1970s. However, decadal trends might hide some important seasonal fluctuations such as in Uttar Pradesh, where rain is primarily a summer phenomenon through the south-west monsoon.

We also collected data for the US, which has a wide range of topographical, ecological and environmental conditions. West of the 100th meridian are the Great Plains with a semi-arid climate and east of the 100th meridian the climate changes with latitude from humid subtropical in the south to humid continental in the north. Tropical cyclones and hurricanes are not uncommon on the east coast, with warm or hot summers, cold and snowy winters and rain in all seasons. Most of our nineteenth-century data are from the north and east regions with a temperate humid climate and hot summers and cold winters with snowfall, though for the twentieth century the data are for the entire country. The mean temperature between the 1810s and 1999 was 8.6ºC (with a rise of 1.6ºC across that period) starting with an upward trend in temperature until the 1940s, then a levelling-off for a decade or two before a new warming in recent decades.[8] Average rainfall fell from around 1130 mm per year during the 1800s and

1810s to just over 700 mm at the start of the twentieth century. It then levelled off before rising from the 1950s onwards.

The five countries selected for analysis also showed different levels of economic and social development over the last 200 years. In France, gross domestic product (GDP) per head increased steadily between 1800 and 1910 but then declined during the World Wars. The urban population only surpassed the rural in the 1930s (Heyberger 2014) and, as late as 1870, 50.6% of the male labour force remained in agriculture (Crafts 1985, 57). According to Heyberger (2014), the population of France before 1850 derived most of its protein from grains: only after that date did the consumption of meat and milk increase. The country's leading crops are wheat, sugar beet, corn, barley, potatoes, fruit and grapes for wine.

In Spain, real GDP per head has been among the lowest of the advanced capitalist countries since 1850. Slow growth was accompanied by delayed structural change, and until around 1900 two thirds of the active population worked in agriculture. The Mediterranean Levant was a region with relatively high labour productivity which "owed much to a combination of a warm climate, irrigation systems, artificial fertilisers and abundant labour which permitted the production of high value crops" (Simpson 1995, 6). Regarding the structure of crops, in Valencia there were oranges, rice, almonds and a varied range of horticultural products; and in Murcia, fruits, vegetables, and lemons: in both cases they were easily exported to European markets. In the 1930s the Spanish diet shifted from a monotonous diet based on bread, potatoes and legumes to a richer system with the consumption of meat, milk, animal fats, fruits and vegetables, positively affecting heights (Cussó Segura and Garrabou 2007).

Mexico is a middle-income country with a GDP per head currently far below that of European countries, though at the start of the twentieth century it was not far below that of Spain. Mexico's economy is inextricably connected to the larger economy of the US. Since 1800 Mexico has gone through periods of sluggish economic performance, war, revolution (1910-1920), rapid export-led growth during the early phases of independence (1821) and the *Porfiriato* regime (1876-1911), and government-managed industrial modernisation (1920-1950), with sustained growth that started around 1940 and lasted until 1980. The share of the active population in agriculture was 62% in 1900, 70% in 1929 and 66% in 1950; it only fell to 50% in 1970 (Prados de la Escosura 2007). The staple crops were corn, beans and squash, and López-Alonso (2012, 13) contends that the dietary habits of the majority of the population barely changed between 1850 and 1950. The central northern part of the country and the *Bajío* region, from which most of our data come, were cattle-raising regions (López-Alonso 2012, 116), which might explain why individuals from these regions were somewhat taller than their southern counterparts from more urbanised and industrial places.

India's GDP per head is the lowest of the countries under investigation: it showed stagnation until the second half of the twentieth century and increased rapidly thereafter. However, the GDP per head achieved in 2000 was similar to the level of Spain in 1950, France in 1900 and the US in 1850. India's economy, despite industrial development in Bombay and Calcutta during the colonial period (1857-1947), has always been tied to the agricultural sector, which has occupied about two thirds of its working population with little change over time (Roy 2005). Indian agriculture was characterized by some of the lowest yields on record and tropical climate and attendant water scarcity limited the prospect of agricultural

commercialization to only a few regions. India's main crops such as cassava, rice, millet, wheat and pulses varied across regions. In Uttar Pradesh, for example, average annual rainfall varies from 25-50 in (64-128 cm) and crops include wheat, millet, pulses, sugar cane and rice (on irrigated land in the drier areas) (Brennan et al. 1994, 276).

The United States had the highest GDP per head of the five countries throughout the period under review. GDP increased steadily between 1800 and 1929, with a fall during the depression of 1929 and World War II and a rapid increase thereafter. In 1800, the US was a largely agricultural economy, with approximately three quarters of the labour force occupied in that sector. Later, industry and services gained prominence at the expense of agriculture. On the eve of the Civil War (1861-1865), agriculture's share of the labour force was 55.8%; it fell to 30.7% in the 1910s, 12.0% in the 1950s and 2.4% in the 2000s (Carter et al. 2006: Tab. Ba-A, 2-18). Olmstead and Rhode (2008: 4-18) argue that, although agricultural development depended on changing technological and market forces, bad weather could affect farm output, and probably affected it more than price changes. They also show that over the last 200 years, corn has been the predominant crop in terms of acreage: between 1910 and 1925, three tenths of national cropland harvested was devoted to raising this one crop. The main crops in the US South are cotton, oats, barley and sugar, and (in the Pacific region) fruit and vegetables. The Central region specialises in field crops such as corn, soybeans and wheat, and north-eastern states produce oats and barley, rye, hay and wheat. Livestock is mostly found in the central and north-eastern regions, in the southern plains and in the south-east.

Table 1: Country level descriptive statistics

Period	Temperature (in °C)					Rainfall (in mm)					GDP per head (1990 Int. Geary-Khamis dollars)				
	France	India	Mexico	Spain	US	France	India	Mexico	Spain	US	France	India	Mexico	Spain	US
1800-09	12.6	na	na	13.5	na	817	na	na	610	1,130	na	na	na	na	1,333
1810-19	12.2	na	na	12.5	7.7	789	1,157	na	599	1,133	na	na	na	na	1,394
1820-29	12.7	23.5	na	13.5	8.4	791	1,171	na	592	1,030	1,202	na	na	na	1,440
1830-39	12.5	23.3	na	13.4	8.2	811	1,074	na	611	1,036	1,298	na	na	na	1,702
1840-49	12.4	23.3	na	13.4	8.2	875	1,088	na	645	1,002	1,502	na	na	na	1,756
1850-59	12.4	23.5	20.2	13.4	8.3	828	1,113	na	635	901	1,681	na	na	1,144	2,082
1860-69	12.7	na	20.5	13.6	8.4	810	1,105	na	614	910	1,920	na	na	1,242	2,368
1870-79	12.6	23.7	20.4	13.5	8.4	817	1,159	na	614	971	2,035	na	na	1,486	2,594
1880-89	12.3	23.6	20.2	13.1	8.3	805	1,182	na	625	937	2,243	na	na	1,659	3,302
1890-99	12.5	23.9	20.3	13.4	8.4	769	1,165	na	603	891	2,603	581	na	1,681	3,613
1900-09	12.6	23.9	20.3	13.4	8.4	762	1,040	681	586	727	2,927	641	1,528	1,862	4,630
1910-19	12.6	23.8	20.4	13.3	8.5	862	1,112	692	607	704	3,135	685	1,751	2,028	5,222
1920-29	12.8	23.9	20.6	13.6	8.7	803	1,066	707	566	719	3,956	693	1,861	2,408	6,174
1930-39	12.9	23.9	20.7	13.7	9.0	886	1,115	734	622	678	4,323	694	1,659	2,283	5,749
1940-49	13.1	24.0	20.9	13.9	8.9	751	1,133	698	596	741	3,552	658	2,116	2,151	9,661
1950-59	13.0	24.2	20.9	13.9	8.9	806	1,118	730	607	703	6,105	669	2,698	2,736	10,556
1960-69	12.9	24.1	20.7	13.7	8.7	857	1,059	766	673	710	9,013	786	3,617	4,575	13,157
1970-79	12.9	24.2	20.6	13.5	8.8	835	1,154	751	623	761	13,067	884	5,041	7,972	16,745
1980-89	13.2	24.3	20.8	14.1	9.1	840	1,133	795	568	750	15,698	1,079	6,132	9,960	20,410
1990-99	13.7	24.4	21.1	14.5	9.3	850	1,165	773	550	792	18,323	1,527	6,389	13,163	24,801

4. Inference from the samples

In order to collect sufficient data for the five countries under review since 1800, we used height data from a variety of sources, including migrants, military recruits and medical surveys (Table 2). For France and Spain we first use conscript data. We then in France use data from the Eurobarometer surveys conducted by the European Commission to monitor public health and opinion in the European member states, and the International Social Survey Programme, a cross-national collaboration to monitor public health in its member countries.

Our data for nineteenth century India are derived from indentured workers who migrated from the present states of Tamil Nadu, Andhra Pradesh, Bihar and Uttar Pradesh to Fiji, Jamaica, Mauritius and Natal to work on sugar cane plantations. Brennan et al. (1997, 194) explained that, although these men came from the lower socio-economic groups, the fact that they "had to pass a stringent medical examination attesting to their good health and physical ability to perform the arduous manual labour required in sugarcane farming" meant that "they were not the weakest and sickliest members of the lower strata." In some years, the selection criteria focused on chest circumference but "recruiting authorities used … height only for purposes of identification and … short recruits were not generally rejected" (Brennan et al. 1994, 277). For the first half of the twentieth century we use nationally representative data from the All India Anthropometric survey carried out in the 1960s (Guntupalli and Baten 2006) covering large parts of North, West and East India. For the second half of the twentieth century we use data from the India Human Development Survey (Desai et al. 2005) which is a nationally representative survey carried out in 2004-2005.

For Mexico and the US we use migrant, military and survey data. Mexican military recruits mostly came from *Bajío* and other central-north states such as Durango, Zacatecas, Nuevo León and Coahuila, with very few from the extreme arid north (Baja California and Sonora) or from tropical southern states (such as Guerrero or Chiapas). They had to meet some basic requirements such as Mexican citizenship, the ability to use weapons, absence of physical and intellectual deficiencies and a height of at least 160 cm (López-Alonso 2012). We also use men who requested passports for travel abroad, and who were more representative of the middle and upper classes of Mexican society. To cover the second half of the twentieth century we use data from the *Encuesta Nacional de Salud y Nutrición*, a nationally representative health and nutrition survey carried out in Mexico in 2012.

For the US, our earliest data are drawn from the records of men who served in the Union and Confederate Armies during the American Civil War. Fogel (1993) showed that the land force that fought for the Union during the American Civil War was representative of the whole of the northern population of military age, using wealth and literacy rates.[9] Using genealogies, he further showed that they experienced the same mortality rates at older ages as the population from which they were drawn. We also used US passport-holder men that represented mostly upper classes, although Sunder (2013, 256) argued that "West Point cadets from 'middle class' family backgrounds exhibit a height trend very similar to the one for passport men." Additionally, we examined a random sample from more than nine million observations from those who enlisted in the army during World War II (WWII). To serve in the army a man needed to be able to read and write in English, be between five and six and a half feet (152.4 and 198.1 cm) tall and weigh at least 105 pounds (or 47.6 kg) (Bleakley et al. 2013). To get a suitable sample for analysis comparable across time and between samples we selected 0.03%

of the nine million WWII enlistees at random. We also use data from the National Health and Nutrition Examination Surveys, a programme of the National Center for Health Statistics to assess the health and nutritional status in the US. Finally, we use a random sample of the two million voter registration cards in Pennsylvania (Wu 1994).

Table 2: Sources and descriptive statistics of height data

Sources: See bibliography for citations. **Notes**: The "period of birth" column only includes the retained observations. *Only data for France has been considered. NHANES - National Health and Nutrition Examination Survey.

Place of birth	Period of birth	Source	Initial obser-vations	Incom-plete or missing infor-mation about place of birth	Foreign birth country	Incom-plete infor-mation about age and/or year of birth	Indivi-dual mea-sured below mature height	Indivi-dual aged above 50 years	Implau-sible measu-rement	Total rejected obser-vations	Retained obser-vations
						Rejected observations					
France	1782-1920	Heyberger (2007)	207,015	173	1,554	1	9,493	n/a	242	11,463	195,552
France	1947-1986	Eurobarometer (1996; 2003; 2010)*	1,506	18	n/a	34	52	553	n/a	657	849
France	1962-1993	International Social Survey Programme	1,382	n/a	30	44	n/a	806	n/a	880	502
India	1810-1896	Brennan *et al*. (1994)	55,206	895	276	182	13,850	53	n/a	15,256	39,950
India	1914-1944	Guntupalli and Baten (2006)	26,186	217	n/a	n/a	n/a	n/a	n/a	217	25,969
India	1956-1984	Desai *et al*. (2005)	74,369	2,384	n/a	4,985	14,919	4,205	n/a	26,493	47,876
Mexico	1842-1958	López-Alonso (2003) (military sample)	7,088	n/a	n/a	n/a	423	53	n/a	476	6,612
Mexico	1876-1915	López-Alonso (2003) (migrant sample)	2,437	n/a	n/a	n/a	67	225	n/a	292	2,145
Mexico	1867-1993	Encuesta Nacional de Salud y Nutrición (ENSANUT) (2012)	40,234	n/a	n/a	3,504	20,029	5,796	n/a	29,329	10,905
Spain	1850-1967	Martínez-Carrión (2002)	161,279	4,475	366	23,049	13,739	n/a	491	42,120	119,159
Spain	1859-1948	Puche (2011)	157,453	34,166	243	34,652	n/a	n/a	n/a	69,061	88,392
US	1815-1845	Costa (2002)	20,463	6,344	2,128	560	1,871	94	n/a	10,997	9,466
US	1812-1845	Fogel et al. (1990)	39,620	842	10,122	1,399	7,778	n/a	n/a	20,141	19,479
US	1815-1846	Steckel (1992)	6,762	29	n/a	21	210	1,620	n/a	1,880	4,882
US	1790-1899	Sunder (2013)	21,700	n/a	n/a	n/a	3,975	157	n/a	4,132	17,568
US	1921-1958	NHANES (1971-75; 1976-80)	20,135	n/a	1,462	392	6,221	6,414	n/a	14,489	5,646
US	1898-1923	WWII Army Enlistment Records (2005)	27,618	4,097	506	5,691	3,351	n/a	4,318	17,963	9,655
US	1886-1957	Wu (1994)	9,362	n/a	n/a	n/a	269	937	n/a	1,206	8,156
Total			879,815	53,640	16,687	74,514	96,247	20,913	5,051	267,052	612,763

The use of height data from previously published studies allows us to examine large amounts of data which have not previously been analysed together or in the context of studying the effects of climate on stature. Table 2 provides a summary of the data collected with the final retained observations, showing the reasons for discarding data in the "rejected observations" columns. These reasons were: that place of birth was not properly recorded; that men had been born outside the present geographical boundaries of the countries under investigation; that age at the time of measurement was unknown or date of birth was not properly recorded; that a man had not yet attained his mature height; and that the height reported in the transcribed dataset was manifestly incorrect (for example 1,630 cm). After eliminating observations in these categories, we had 612,763 separate observations which could be subjected to further analysis.

Military organisations in non-conscript armies and during peace-time usually applied minimum height requirements, which meant that they excluded the shortest members of the populations from which they were drawn (Fogel et al. 1983). If a particular climatic variable is associated with shorter heights, and if shorter individuals are excluded from the dataset, we will have less variation in heights and some part of the height distribution will not be analysed, which is likely to obscure the true relationship between climate and stature. We used the cumulative distribution function of heights to detect possible points of truncation and then explored how far the samples deviated from a normal distribution with the Normal Quantile Plot and the kernel density distributions for different time periods (unreported here). We found that in the nineteenth century French and Mexican military samples there was evidence of truncation due to minimum height requirements and therefore for these two samples we used truncated regressions to account for truncation in the height distribution (Wachter and Trussell 1982). We used truncated regression to estimate the covariate effects of climate on heights within truncated samples assuming a truncated normal distribution to estimate the standard errors. For Mexico we used the truncated point of 160 cm also described in López-Alonso (2012) and in France, the truncated points by place and year of measurement described in Heyberger (2007, Table 1, 232-3). For the Mexican case, the sampling of military recruits and passport holders (who were taller than the soldiers) might cause, at most, small compositional effects, as the proportions of both groups are roughly maintained and both show the same overall height development.

Sometimes it was not possible to determine the year of birth, because information about the year of birth, age and year of collection was missing or improperly recorded. We also checked for heaping on age with age histograms and the Whipple and Myers' Blended Indices and only found evidence of age heaping in the Indian datasets. Age heaping is a phenomenon more common in poorly-educated societies (which are also likely to be short) and "heaping is repeatedly observed in all censuses and [modern] surveys in some countries, and cannot be eliminated even with special training of interviewers" (Pullum 2006, 2). Yet Brennan et al. (1997, 190) claimed that the age data for the nineteenth-century Indian migrant sample were reliable. Nevertheless, in India the greater imprecision in the reporting of age may increase the risk of individuals being allocated to the wrong birth years and hence obscure the relationship between height and climatic conditions at the time of birth.[10]

We link climatic data to the year in which an individual was born because it has often been claimed that this is the period in which growth is most sensitive to environmental and nutritional shocks (see e.g. Tanner 1962). Moreover, focusing on the first year of life allows us

to identify members of the same cohort, whilst acknowledging the fact that final or mature height reflects the cumulative impact of environmental and nutritional conditions throughout the period of growth. The pattern of human growth in modern well-nourished populations that have grown in a conducive environment shows that a man might attain his mature height at the age of 18-19 years. However, it is possible that growth may be delayed until the age of 20-23 years, or even later in some instances, if environmental or nutritional conditions are less conducive (Tanner 1962). Therefore, in order only to consider males that stand at mature height, we first estimated the age at which maximum height was attained. We carried out an exploratory analysis of the confidence interval graphs for age groups, proceeding with an analysis of variance test and a post-hoc Bonferroni test at the 90% confidence level to identify the yearly age groups with statistically different mean heights.

Some of our data come from military records in which individuals were measured mostly at the ages of 18-22 years, giving an over-representation of young individuals who may not have reached their maximum height. This applies to Spain and France, so for these countries we have compared our height trends with those derived for men aged between 30 and 40 years from twentieth century surveys and heights standardised by age: the trends are similar.[11] After comparing the series with those standardised at the age of 21 years by Martínez-Carrión and Moreno-Lázaro (2007, 151) we agree with their conclusion that in Spain "changes in recruitment age scarcely affected the trend in physical stature."

The dataset also contains older individuals: as human beings are known to start shrinking in their late-forties or early-fifties, we have excluded individuals who were measured above the age of 49 years. A very few observations showed individuals to be abnormally short but no-one in the sample was impossibly short. For instance, a 40-year-old man born in Granville (New York), who enlisted in the Union Army in February 1864 for three years, was 121.9 cm tall and weighed 50.1 kg. While this could be a recording error, it is also possible that this man was suffering from achondroplastic bone-growth disorder or a similar condition and we have retained his information because the reported height is within the range of possibility.

Figure 2 reports the resulting estimated heights of our samples. The average heights of successive French cohorts since 1800 have grown slowly but with an acceleration in the rate of improvement: 163.5 cm in the 1800s to 165.2 cm in the 1850s, 168.2 cm in the 1900s and 179.2 cm in the 1980s. There were some temporary reverses: for example, "heights … decreased in Sélestat, and in Saint-Yrieix and Bellac between the 1810s and 1820s, when France was undergoing a prolonged economic crisis" (Heyberger 2007, 240). In Spain mean stature was 161.1 cm in the 1850s, 164.3 cm in the 1900s and 168.6 cm in the 1950s.

In India, average heights show a cyclical pattern of increase in the early nineteenth century (of about 3.1 cm, on average), followed by a decrease in the middle of the century and a moderate increase between the 1860s and 1870s. Since the 1880s there has been a linear monotonic increase in stature of around 0.3 cm per decade. In the 1830s Indian heights were very similar to those in France (at 162.8 cm) and Indians were taller than Spaniards until the birth cohorts of the 1880s.

In Mexico during the *Porfiriato* period (1876-1911) heights stagnated at around 165-166 cm, then the average value of the heights declined by almost 2 cm in the 1920s to 164.3 cm, the period of decline coinciding with the Revolution (during the 1910s) and Cristero War (1926-1929). The nineteenth century levels were not recovered until the 1940s (at 165.7 cm)

when a welfare system was developed. Thus, although the Mexicans who were born during the 1870s and 1880s were nearly as tall as contemporaneous Frenchmen, the birth cohorts of the 1980s were more than 11 cm shorter (167.3 cm as opposed to 179 cm).
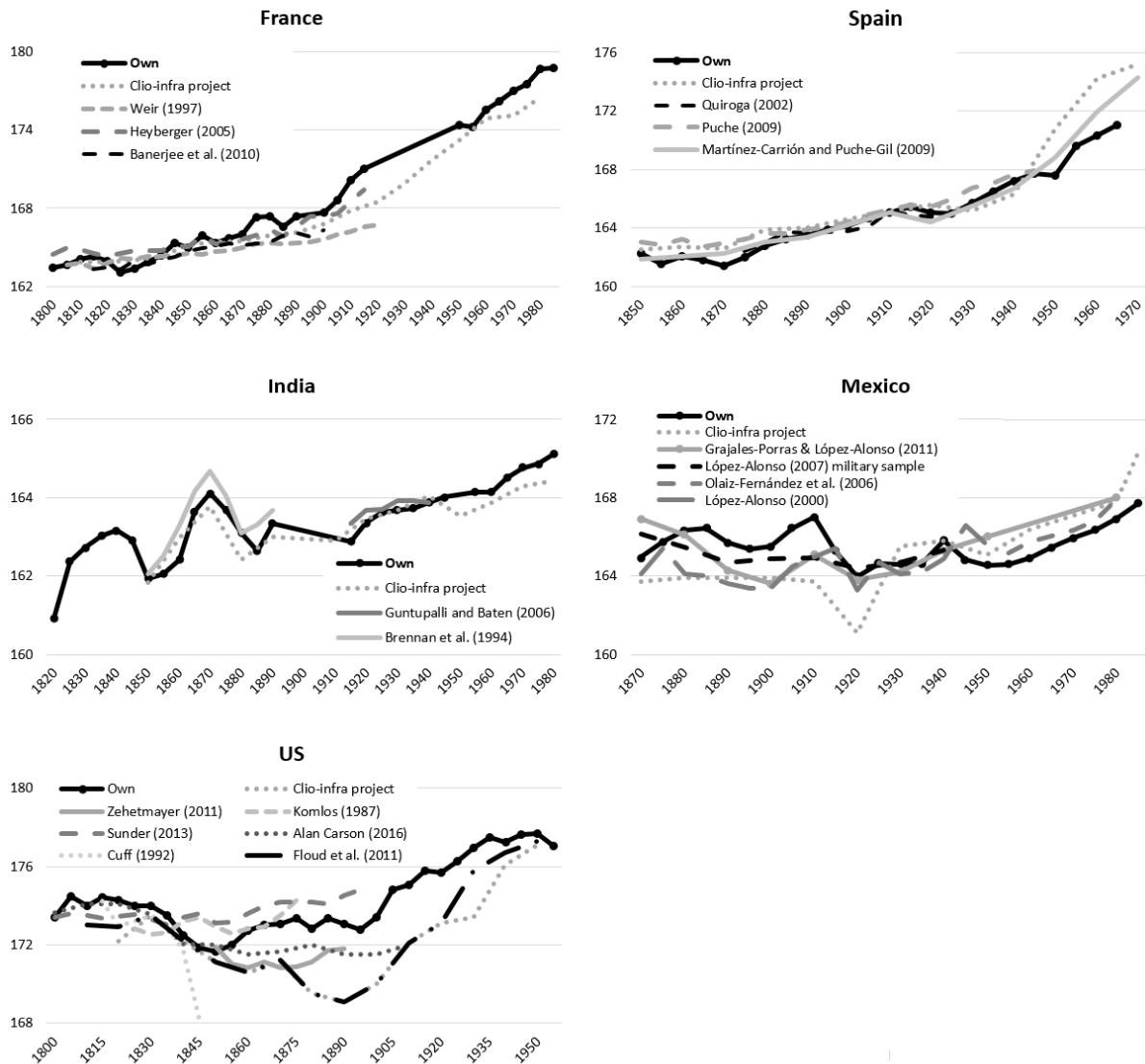
The average heights of men born in the US stagnated between the 1800s and the 1830s (at 174.0 cm) then fell in the 1840s and did not increase consistently until the end of the century.[12] Floud et al. (2011) argued that there were other environmental factors on the side of claims on food intake that substantially reduced the positive impact of diet on height during this period. During the twentieth century heights started to increase rapidly (to 178.2 cm in the 1950s) due to public health interventions, better medical technology, higher incomes and reduced disparities between rural and urban populations (Floud et al. 2011). As Figure 2 shows, there is disagreement among previous researchers as to the trend in US heights between around 1860 and 1930. The divergence in the series derives from the use of different sources. Figure 2 includes data from Sunder (2013) based on upper-class migrants, Zehetmayer (2011) based on US Army recruits and Carson (2016) based on prison inmates, as well as a series from Floud et al. (2011) which is based on that originally described by Fogel (1986), which used interpolated data from the Ohio National Guard.

Figure 2 also shows the time trend in heights from other comparable studies of each of the five countries. For France, Spain and India our series are very close to all the previous series with which we have compared them. For Mexico the correspondence is very close after 1930, but for the period from about 1880 to about 1910 the men in our sample are rather taller than those in some of the other series. The US shows the greatest variation between the series produced in previous research. Our series falls close to or within the range spanned by previous series, but between about 1860 and 1920 it lies substantially above that of Floud et al. (2011).

In view of the fact that we have collected our data from previous height studies, our results are, as expected, very similar to those reported from the authors or studies from which we have collected the data. In Mexico and the US, because we pooled data from multiple sources, it is possible that stature changes over time in our study could deviate from other studies as the composition of our pooled data could differ from studies using part data. Our nineteenth-century Mexican series includes data from migrants and military troops and for the twentieth century we add the data from the ENSANUT (2012) while data from Olaiz-Fernández et al. (2006) are from the previous wave (2006). For the US we can say that our series relates closely to other measures of wellbeing, such as the expectation of life at age 10 years reported by Costa (2015) and Fogel (1986) or the crude death rates reported by Floud et al. (2011) (See Appendix A2). Additionally, if composition effects were important in the US, they should be greater in the first half of the nineteenth century, when we pooled data from four different authors/sources. However, in this period the discrepancies are minimal. Unfortunately, we cannot repeat the historical comparison of our height estimates with other health indicators in Mexico, because these additional variables do not exist.

Figure 2: Reported height estimates from different sources (in cm)

Sources: See bibliography for details. For Clio-Infra project see www.clio-infra.eu, accessed 11 April 2017.

5. Climate data

During recent years meteorologists have used instrument readings to reconstruct climatic data for the twentieth century for the whole world, and back to the 1750s for the European countries.

These data are commonly reported on the basis of grids superimposed on the earth's surface which interpolate station data and other geographic information over a grid of a certain resolution. Most of the data come from ground stations. Dell et al. (2014, 749) argue that "in general, gridded datasets are a good source of temperature data for economic analysis in that they provide a balanced panel that potentially adjusts for issues like missing station data, elevation, and the urban heat island bias in a reasonable way."

Temperature is the degree or intensity of heat present in an element and precipitation is the condensed moisture of the atmosphere falling visibly in separate drops, regulating the

circulation of water in the environment. The gridded data are reported as deviations from current values, or anomalies, but we converted them to actual temperatures. A temperature anomaly of 1ºC at point i in year t means that the temperature at i was 1ºC higher during t than the mean temperature at i over the period 1950-1980.

We used the Berkeley Earth Surface Temperature (BEST) dataset that reports the mean monthly daytime temperatures from 1753 to 2000 at 1º by 1º grid resolution.[13] For rainfall, from 1901 until 2000 we use a global monthly dataset at 0.5º by 0.5º grid resolution from the Climatic Research Unit (CRU) Time-Series (TS) version 3.21 (Harris et al. 2014). We have been able to extend the dataset for France and Spain at the same resolution using data for the period 1766-1900 from Casty et al. (2007), for India using regional data from the Indian Institute of Tropical Meteorology from 1813 to 1900, and for the US using the weather stations reported in Carter et al. (2006) since the 1820s. The information gathered amounted to more than 450 million climatic points since 1750.

For temperatures, we used the BEST dataset as this is the only global dataset with data for the nineteenth century (for instance, data from the CRU TS begin in 1901). For precipitation, we use the data for the CRU TS for the twentieth century and since there are no global data for the nineteenth century we had to combine them with other datasets or data directly from the stations as described in the previous paragraph. As a robustness check we test for the choice of the climatic data, and we have been able to replicate the results for the twentieth century using the data from CRU TS. Yet, despite our data being among the most widely used datasets, for the nineteenth century, we cannot test our estimates for precipitation as no other climatic data exist for this period.

In discussing the suitability of gridded datasets in statistical analysis, Dell et al. (2014) identified two potential issues: problems associated with the analysis of 'short periods' of time and problems when there are more grid cells than underlying stations. They suggested that this second issue "would not necessarily compromise the analysis if the gridded data are aggregated to large enough units (e.g. countries), it can pose challenges for inference regarding smaller geographic units, particularly in areas with sparse coverage, such as Africa." For the first concern, we use yearly instead of monthly data and control for the amount of volatility in our models with the method of the rolling regression. For the second concern, although climatic scientist accounted for missing meteorological stations in less densely population areas when constructing the gridded networks, we grouped individuals across space and time and weighted temperature or precipitation in the country by the number of individuals and their location in a given year (see also next section).
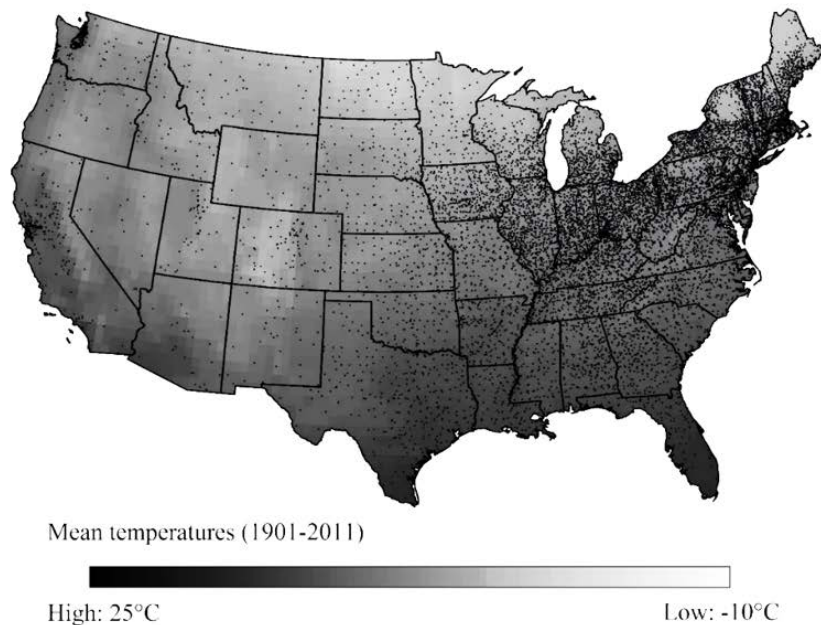
6. Connecting humans and climate

In order to assign to individuals the temperatures and precipitation that they were exposed to during their years of birth, we used GIS software to perform a spatial join by location with the Euclidean distance between the place of birth and the climatic grid point.[14] As an example, Figure 3 illustrates how individuals have been geocoded by the place of birth in the US (black dots) and how each individual was assigned climatic information on the basis of the coordinates of each climatic grid cell. Although in most cases place of birth was recorded in a quite detailed fashion (usually to the level of neighbourhood, village, town or county), in some cases we had

only the name of the district or state. Precision is necessarily lost in the latter situation, but this does not hinder the analysis greatly as inland meteorological information between contiguous grids does not differ significantly at 0.5º by 0.5º or at 1º by 1º cell resolution.[15] Temperature and precipitation are linked to each man in the following way: for man *i* born in place *k* in year *t* we attach the gridded temperature and precipitation in the year *t* that is closest to place *k*, using GIS software. The assigned temperature and precipitation thus vary in accordance with the place and date of birth of the men in our sample.

Figure 3: Connecting climatic grid cells with individuals in the US.

Sources: For height data see Table 2; temperatures from Berkeley Earth Surface Temperature dataset (www.berkeleyearth.org, accessed 11 April 2017). **Notes**: Place of birth can represent a group of individuals when their place of birth was reported using the same name.

Mean temperatures (1901-2011)

High: 25°C   Low: -10°C

We then examine the extent to which the relationship between stature and the two meteorological variables has changed over time within each of the five countries, using a technique known as rolling regression. This method involves calculating the coefficients for the regression of height on either temperature or precipitation in moving windows of a fixed size through the sample and shows whether there is a cross-sectional relationship between a meteorological variable and stature over a defined geographical area within a specific period. To see whether the relationship changes over time we repeat the regressions for successive periods in fixed windows where the length of the window allows us to control the volatility of the climatic variables.[16] To establish the best window for analysis we selected 15-year windows using the middle year as the target year. In comparison to windows of 1, 3, 5, or 11 years, a 15-year window reduces the amount of volatility and shows the same major patterns as shorter windows. In comparison to windows of 21 and 31 years, it involves the discarding of fewer data at the beginning and end of each sequence for which data are available. In turn, this method minimises the composition effects of pooling data from different samples as the resulting estimates show a sequence of overlapping cross-sectional relationships arranged over time.

We estimate the following equation:

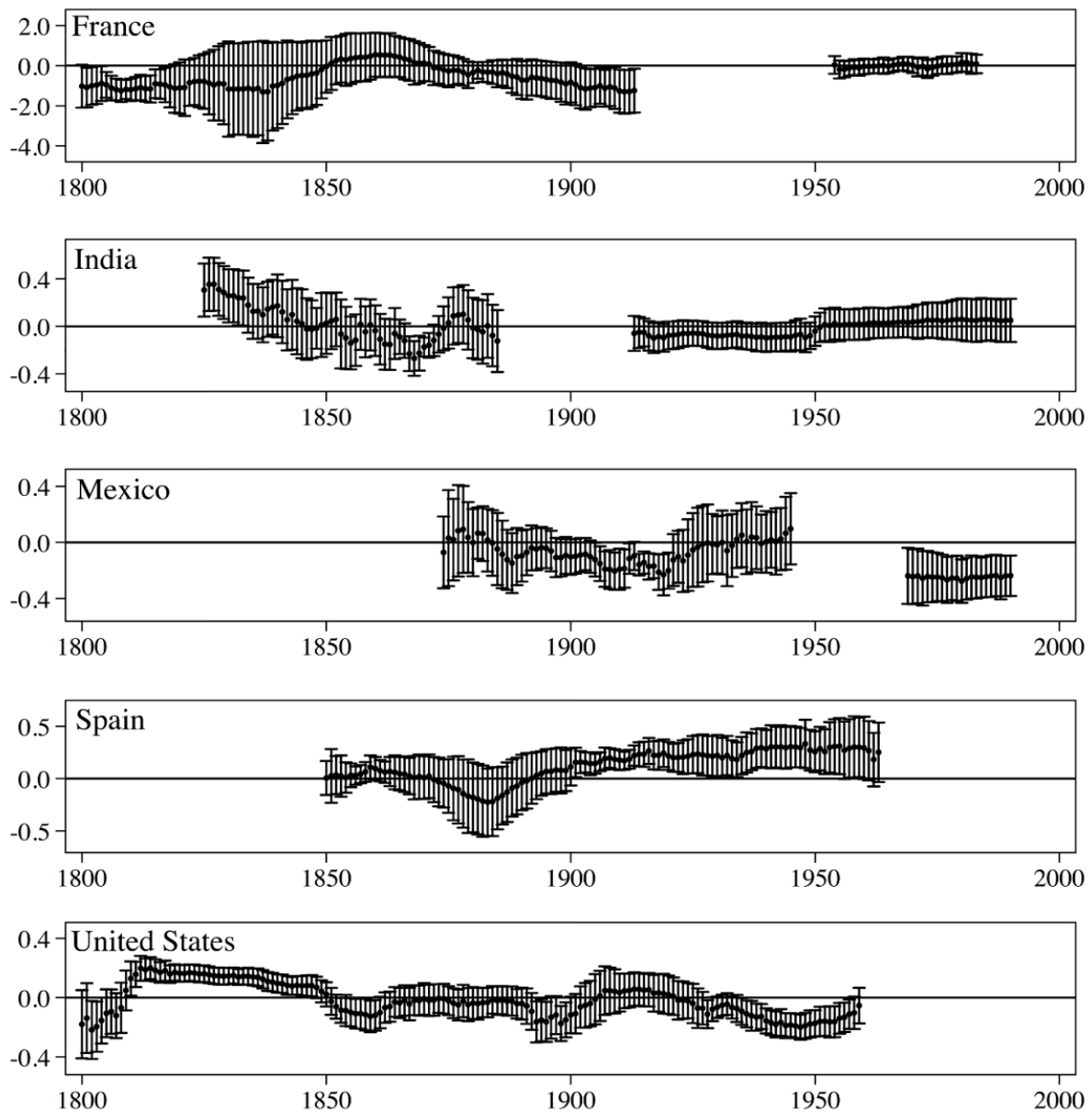$$y_{ikt} = \alpha_{\tau k} + \beta_{\tau k}{}^{T} c_{ikt} + \varepsilon_{\mathrm{ikt}} \tag{1}$$

where y_{ikt} is the dependent variable, stature, for case i ($i = 1, 2, \ldots, N_k$), in country k ($k = 1, 2, 3, 4, 5$), belonging to year t ($t = \tau, \tau+1, \ldots, \tau+14$). The equation refers to overlapping intervals labelled τ ($\tau = 1, 2, \ldots, P$). Additionally, $\alpha_{\tau k}$ is the intercept for country k in overlapping interval τ, c_{ikt} is the climatic variable of interest, $\beta_{\tau k}$ is the coefficient on the climatic variable for the window τ and ε_{ikt} is the error term. We computed robust standard errors to take account of the clustering in the data, since several individuals can share the same temperature and precipitation grid cells.

7. Climate effects on stature

Figure 4 presents the estimated regression coefficients with their 95% confidence intervals over time for a succession of overlapping 15-year periods when temperature is the climatic variable. In France between 1800 and the early twentieth century there was generally a negative relationship between mean temperature and height (warmer temperature associated with shorter stature), though the association turned positive for a time in the 1850s and 1860s. The data available after the 1950s suggest no significant relationship. In Spain there was a negative association during the 1880s, but a consistent and increasingly strong positive association from the early-1900s onwards. In India there was a positive relationship during the 1830s and 1840s but this turned to a consistent negative association from the 1850s, and it was not until the 1950s that a positive relationship emerged. In the US, we find a positive association between temperature and height between the 1810s and 1850s, followed by a mainly non-significant relationship until the 1930s when a negative relationship appeared. In Mexico the association was generally negative but it was only statistically significant for a couple of decades in the early twentieth century. A stronger negative association emerged after the 1960s.

Figure 4: Results from rolling regressions of impact of temperature on stature.

Sources: For height data, see Table 2; temperatures from Berkeley Earth Surface Temperature dataset (www.berkeleyearth.org, accessed 11 April 2017). Notes: Standard errors in these regressions have been computed after taking account of the clustering in the data.

How might these results be explained in the context of the theoretical framework discussed earlier (Figure 1)? For the early-nineteenth century US, Floud et al. (2011, 301) said that the combination of abundant farmland and favourable climates was a major cause of the foundation and development of the early American 'free land' economy. It may have been easier to grow crops in warmer areas as heights appear to have been positively correlated with temperatures. Then we observe an attenuation of this relationship from the mid-nineteenth century until the 1930s, as the share of agriculture as a proportion of economic activity decreased whilst economic growth and technological advances occurred concurrently. "Compared to farming, manufacturing depended less on seasonality or climate changes and

more on technology and the quality of machines, tools, and operating power" (Floud et al. 2011, 320).

However, Figure 4 also suggests that during the 1930s a negative relationship emerged which might be linked to the "dust bowl" phenomenon of a semi-arid climate with dust storms and warm temperatures that greatly damaged the ecology and agriculture of the central and southern US. This phenomenon had an uneven impact across the US, with a particularly damaging effect on a belt of states ranging from the Dakotas through Nebraska, Colorado, Oklahoma, parts of Texas and New Mexico between 1930 and 1936 (Landon-Lane et al. 2011, 81-2; Gutmann et al. 2016, 717-8).

In Spain, heights were generally greater in warmer areas. As Simpson (1995, 256) notes: "about four-fifths of Spain's agricultural land suffered from seasonal droughts and low crop yields at the turn of the twentieth century. By contrast, the relatively high labour productivity in parts of the Mediterranean owed much to a combination of a warm climate, irrigation systems, artificial fertilisers and abundant labour which permitted the production of high value crops."

However, for a period in the 1880s this association was reversed. The 1880s witnessed an agricultural decline with the disruption of the previous agrarian expansion (Garrabou i Segura 1975). The effects were felt largely in warmer and irrigated areas: "in the 1880s, the fall in demand in Europe, the effects of the pests in the agriculture, the climatic irregularities with droughts and floods, and the problems of adapting to the enlargement of the [global] market, were felt in most of the irrigated areas" (Martínez-Carrión 1988, 155). This may have caused a reversal of the association between temperature and mean height. In Catalonia, Ramón-Muñoz (2009) also found that the agricultural crisis affected irrigated areas to a greater extent with a decline in heights between 1870 and 1895 of about 1 cm. In addition, warm temperature is an important determinant of malaria, and this may also have had an effect on stature (Martínez-Carrión 1994). The argument here is that the higher incidence of malaria was always acting to suppress the height of those who grew up in warmer areas. For most of the period since 1850 until the eradication of malaria in Spain in the early twentieth century, this effect was more than counteracted by the greater success of agriculture in these areas, but during the 1880s the agricultural crisis prevented this counterbalancing of the malaria effect; indeed, differentials in agricultural production may temporarily have reinforced it.

In Mexico, we find a negative association between temperatures and stature from the 1890s to the 1920s and after the 1950s. Beyond the temperate centre, warm areas in the north and the south were less conducive to growing crops (Guerrero Compean 2013; López-Alonso 2012). For example, when Fogel (1989, 318) evaluated the warm areas of north Mexico he said that "the arid lands acquired from Mexico were unsuitable for cotton and of dubious value for other crops." Warm areas in the south were also more prone to dengue fever and malaria (Rodriguez-Abrego et al. 2010). However, the negative relationship disappeared temporarily after the Revolution and the Cristero War, a period that was followed by the development of the welfare system, expansion of trade and 40 years of sustained economic growth. During this period the government imported grain from abroad, mainly from the US, to mitigate the effects of crop failure (López-Alonso 2012, 189). Since the 1950s the negative association between temperature and stature has re-emerged (Agüero 2014), which may be associated with the rapid

increase in temperatures and the increase in the frequency of the El Niño Southern Oscillation (ENSO).

In India, we find that men who were born in colder areas during the second quarter of the nineteenth century were shorter than men born in warmer areas but this relationship appears to have largely disappeared after 1850. During the first half of the twentieth century, there was a weak negative relationship between temperature and stature, possibly due to the vulnerability to high temperatures of yields in the crops which were then grown (Easterly 2007). However, across the twentieth century any negative pattern in warm areas was overturned by the Green Revolution, which raised productivity and living standards in rural areas (Roy 2005).

Finally, we find that in nineteenth-century France people living in warmer areas were shorter, except for the decades of 1850s and 1860s (see also Dupin 1827 and Heyberger 2014). Yields of cereal crops were substantially higher in the colder northern areas in the early nineteenth century and, although there was progress in the central areas of the country, these regional disparities continued into the second half of the century (Newell 1973). However, the height differential between colder and warmer areas was reversed during the second half of the nineteenth century, in that people who were born in colder areas grew up to be shorter than people born in warmer areas. Given the lack of fluctuations in temperatures seen in Table 1, this reversal might be connected to technological changes in agriculture (Toutain 1961). Newell (1973) argued that although growth in productivity occurred in the cold north during the first half of the nineteenth century, improvements such as the introduction of mixed farming and crop rotation had a greater impact in the warm south during the second half of the century. These improvements helped to reverse the negative association between height and temperature of the 1850s and 1860s.

After 1950 no relationship is observed, suggesting that in recent periods the relationship between temperature and stature has become weaker as a result of the technological changes which Fogel and Costa (1997) described. As seen in the agricultural revolution that occurred in the nineteenth century along with the railroad, financial and commercial expansion, the percentage of people living in cities of more than 10,000 inhabitants rose from 8.9% in 1800 to 18.1% in 1870 (Malanima 2010, 260). Schultz (1951) hypothesised that the effect of the increases in urbanisation and industrialisation on agriculture may operate through increased market effectiveness and reduced dependence on domestic agriculture as a source of food. There is clear evidence of a dramatic increase in food imports in France from the early twentieth century (National Bureau of Economic Research 2017), while Floud et al. (2011) reported that in France real wages increased by 192% in the period 1945-1993.

Figure 4 also suggests that the beta coefficients from the nineteenth century French data regression equations are greater than the coefficients for the other countries studied. It is not entirely clear why this should be the case, although we can suggest a number of possibilities. First, there is a limit to the absolute impact which climate can have on stature, because variations in stature are limited by human physiology. Given the bounded nature of the potential impact of climate on height, the magnitude of the coefficients in each country will be affected by the absolute variability of the climate in that country over space and time. The climate within France has a lower variance and a smaller range in both temperature and precipitation than that of Mexico, India or the US. It may therefore not be surprising that any differential in stature in France would be associated with small differences in mean climate,
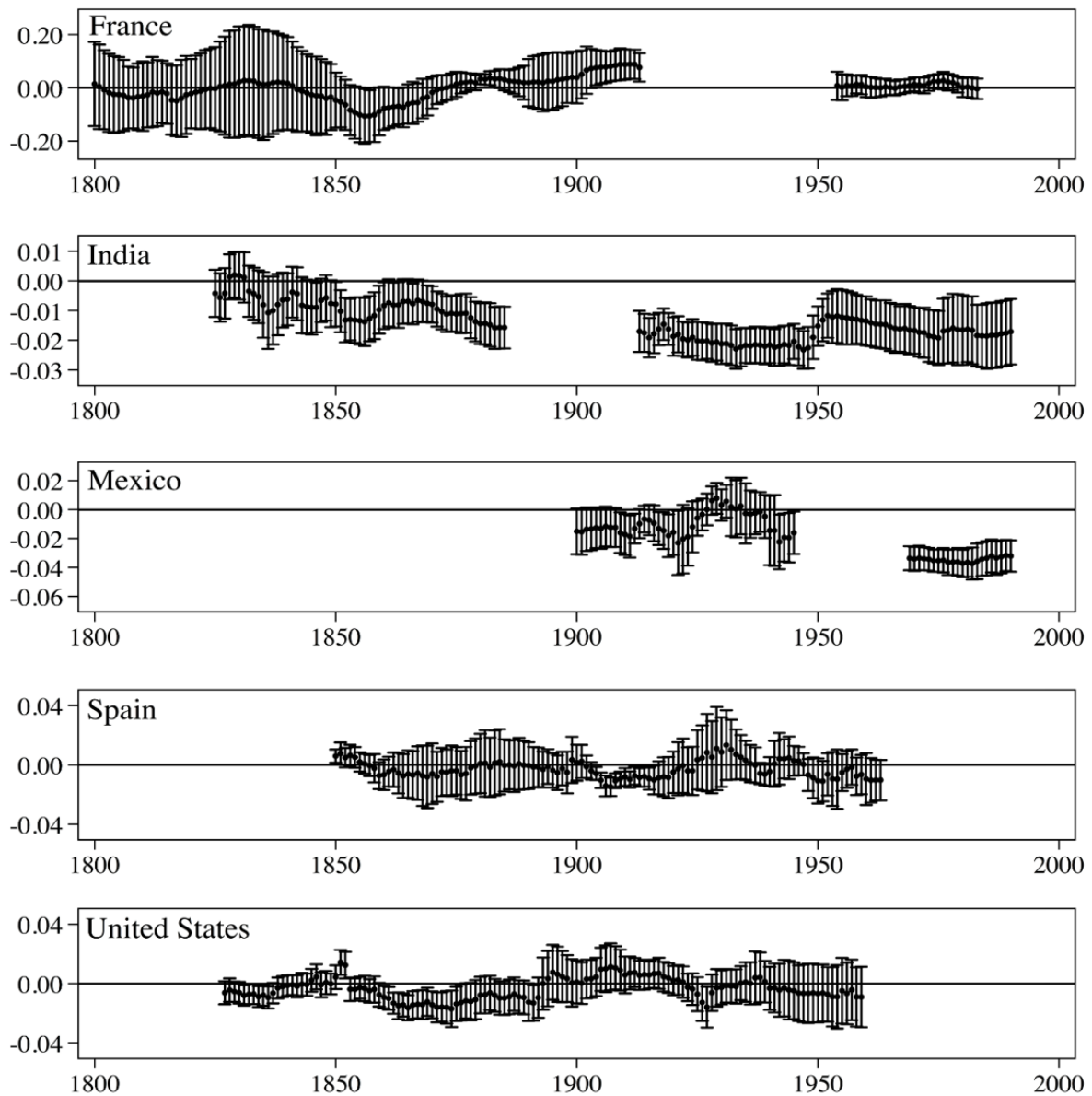
and that the coefficients linking stature to these climatic variables would be larger in France than in the other countries.

Second, the association between differences in climate and crop yields is non-linear, so it is possible that the same absolute amount of difference in mean temperature or average precipitation has different effects in different countries. Third, the association between climate and stature in France may have been compounded by the independent effects of other variables, in ways that were less true elsewhere.

We turn now to the results for the effect of precipitation on stature (Figure 5). In France the impact is negative between the 1840s and the 1870s and this is followed by a positive association between 1870-1910 and no association in the second half of the twentieth century. However only for a brief period in the 1850s and at the beginning of the twentieth century is the association statistically significant. Both the size and the strength of the association between precipitation and stature in Spain vary over time, but after 1900 the association becomes mostly negative. In India the association turns negative during the nineteenth century and remains so throughout the twentieth century. In Mexico a weak negative association seems to exist between the 1900s and 1920s and this becomes more pronounced in the second half of the twentieth century. In the case of the US the negative association during the nineteenth century ceases in the 1890s.

Figure 5: Results from rolling regressions of impact of precipitation on stature.

Sources: For height data, see Table 2; precipitation data from Harris et al. (2014), Casty (2007), Carter et al. (2006) and Indian Institute of Tropical Meteorology. **Notes**: Standard errors in these regressions have been computed after taking account of the clustering in the data.

In France, men who were born in wet areas during the middle of the nineteenth century were, on average, shorter than those born in dry areas, consistent with a negative relationship between persistent levels of rain and stature in *ancien régime* France (Komlos 2003) due to the negative relationship between abundant rainfall and crop yields (Le Roy Ladurie 1971). The reversal of this relationship during the final quarter of the nineteenth century may be explained by a combination of lower precipitation levels and new tariffs. Bassino and Dormois (2010, 37) emphasise the importance of the imposition of new tariffs on agricultural imports in the 1880s and assert that rainfall was a very important factor in explaining the development of wheat production under the tariff. Given the reduction in rainfall between 1840 and 1900 (Table 1) and restrictions in trade, they pointed out that agricultural depression was felt more acutely

in dry areas, where "wheat cropping became uneconomical in marginal areas that had been cultivated during the comparatively wetter and colder period up to 1870" (Bassino and Dormois 2010, 25). Bassino and Dormois were writing mainly about the Mediterranean littoral whereas our data derive mainly from central and eastern areas. Nevertheless, tariffs on agricultural imports were imposed nationally and so affected agriculture in all areas of the country.

The association between rainfall and stature in Spain is weak and rarely statistically significant. Our sample is mostly taken from the Mediterranean Levant, an area where irrigation was widely practised in agriculture (Simpson 1995). It may have been that irrigation weakened the force between rainfall and heights in areas that employed irrigation systems, a hypothesis we are examining in current work.

In the US in the nineteenth century, people born in wetter areas were, on average, shorter than those living in dry areas. However, in the twentieth century no association is observed. According to Bleakley and Hong (2017, 773) "hot and rainy short-term weather was less favourable for producing agricultural output in the late nineteenth century than it was in the late twentieth century and that the adaptation of farm output value to weather occurred more-or-less steadily across decades."

Thus, rapid change in the geographical pattern of crop production in agriculture, with technological adaptation in wet environments through drainage, fertiliser use, the selection of the crops, and hybrid seeds may have mitigated the negative effects of high precipitation on agricultural productivity (Floud et al. 2011, Hong 2011, Olmstead and Rhode 2008). Moreover, in the nineteenth century wet areas were favourable to malaria transmission (Hong 2011) and malaria was prevalent in a vast area of the US including the whole of the east, south, and mid-west apart from Appalachia and New England.

From the evidence available for Mexico during the twentieth century, it seems that the relationship between precipitation and stature resembles the relationship between temperature and stature: a weak negative association between the 1900s and 1920s that was stronger after the 1960s. This may be the result of the increasing levels of rain in Mexico after the 1940s as seen in Table 1 (Guerrero Compean 2013). Heavy rains may have increased the burden from diseases felt in Mexico. For example, the proportion of children under five who had diarrhoea in the two weeks preceding an interview conducted by the *Encuesta Nacional de Salud y Nutrición* was higher in wet areas (Díaz Ortega et al. 2012). Heavy rainfall in wet areas may have led to hydrological erosion and the higher frequency of the ENSO may have contributed to negative effects on corn and the production of other crops (Conde et al. 1999).

The population of nineteenth century India lived close to the margins of subsistence. In accounting for the Great Divergence, Parthasarathi (2011, 76) argued that in India "shortfalls in food production, whether due to climate or biology, were … frequent, as were the famines that often accompanied harvest failures." Therefore we might expect considerable sensitivity of heights to climatic fluctucations. It seems that the heights of people who are born in India have, since at least the mid-nineteenth century, been more sensitive to rainfall than temperature, and that people who are born in wetter areas have tended to be shorter than those born in dry areas. This has been found using modern nationally representative data: according to Deaton (2008), taller men are found in the states of Jammu and Kashmir (168.3 cm), Rajasthan (167.5 cm), Punjab (168.6 cm) and Haryana (168.1 cm), being regions which receive annually less than 700 mm of rain. Men living in states that receive more than 2,000 mm of rain per year

tend to be shorter (166.2 cm in Goa, 163.6 cm in Assam, 161.6 cm in Tripura, 163.3 cm in Mizoram and 157.2 cm in Meghalaya). Our results suggest that this pattern is long-standing.

This is not surprising due to the nature of the crops grown in dry and wet areas and of the structure of farming in the two areas (Roy 2016). Irrigated zones produced crops for export; people living in rain-fed areas often struggled to subsist (see also Tomlinson 1996). Disease was also more prevalent in wet areas, both in the form of malaria and gastrointestinal infections, and influenza (Donaldson and Keniston 2014). As Brennan et al. (1994, 204-5) observed: "malaria and gastroenteric illnesses affected many among the population, including the children. It is not difficult to understand reduced final adult heights, given low childhood growth rates arising from illness and uneven food supply and compounded by problematic nutrition into the early adult years."

Taken together, these results suggest that the impact of climatic variations on stature has diminished over time and is now much more apparent in low- and middle-income countries than high-income countries. This supports the view that, over the course of the last two centuries, economic and technological changes have played a major role in changing the relationship between human beings and their environments in many parts of the world. However, we cannot exclude the possibility that changes in either temperature or precipitation may have affected people in different or even contradictory ways, leading us to underestimate the impact of these variables when the results are averaged across regions. We have tried to explore this by modelling the relationship in different ways, using quadratic or higher-order polynomials (see Appendix A3). The majority of the results are broadly consistent with those obtained from our initial analysis, but the results for France are more mixed. This may reinforce some of the concerns raised during our earlier discussion of the size of the coefficients in our French results, and suggests that further research may be needed in this area.

8. Conclusion

The main aim of this article has been to describe changes in the relationship between temperature and precipitation, on the one hand, and average male stature on the other by looking at the impact of variations in the climate. We have shown how this relationship varied over time and between countries. In what are now wealthier or more "developed" countries, the relationship has become much weaker over time, but it remains important in poorer countries and in countries which have continued to be heavily dependent on domestic agriculture.

Fogel and Costa (1997) developed the concept of "technophysio evolution" in order to capture the extent to which human beings had gained increasing control over their environments since the early eighteenth century. The main elements of this process included breakthroughs in manufacturing, transportation, trade, communications, energy production, leisure-time services and medical provision, alongside changes in agriculture (Fogel and Costa 1997). However, much more work remains to be done to identify the particular combinations of changes which had the greatest impact on developments in individual countries.

In addition to considering the relationship between climate and stature in the past, it is also important to consider the possible implications of these changes in the future. Although average temperatures have increased in each of our countries over the course of the last two
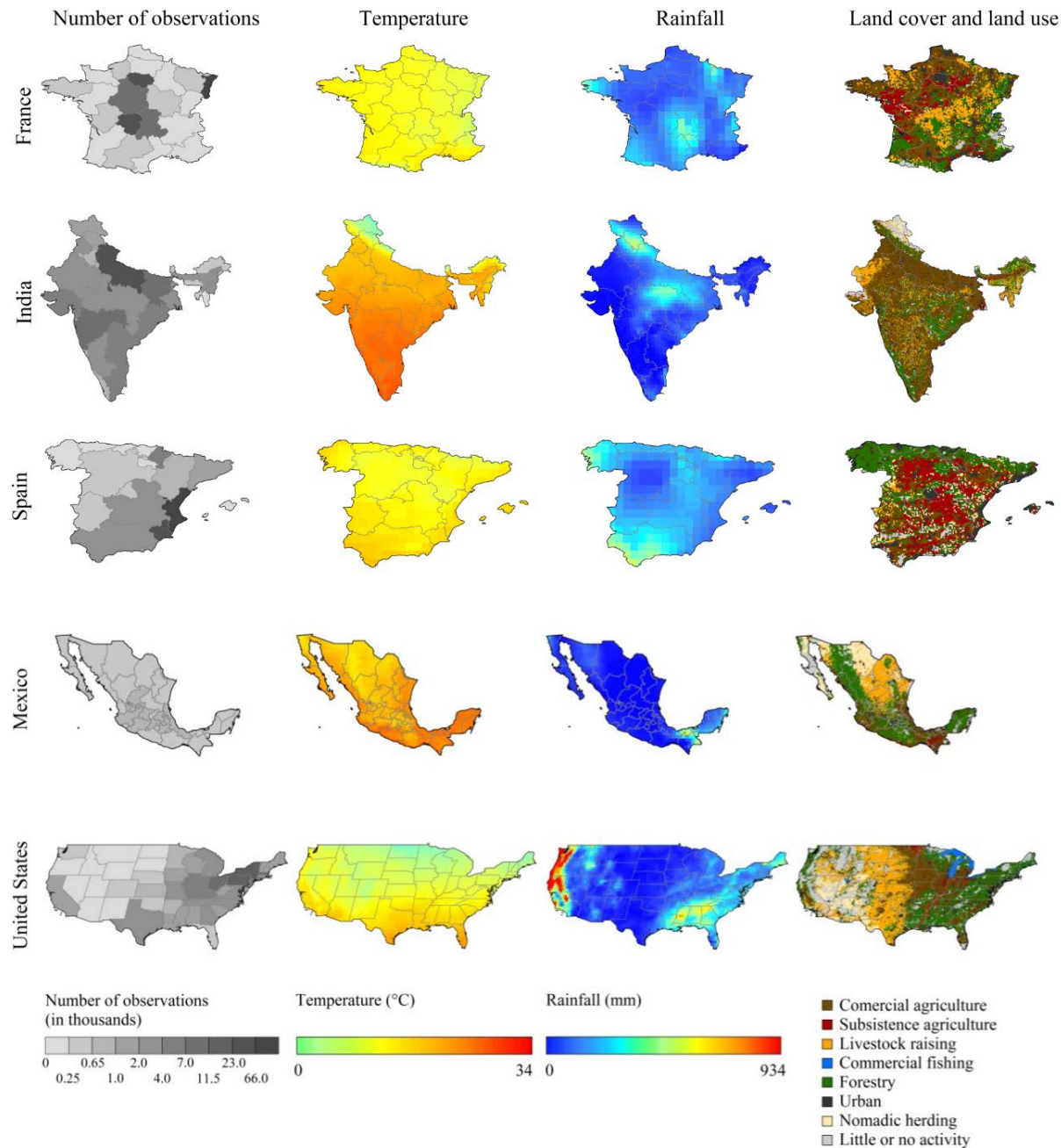
centuries, the pace of change in at least four of these countries—France, India, Mexico and Spain—was quite slow up until the early years of the twentieth century, whilst temperatures have increased much more dramatically in France, Mexico, Spain and the United States since the 1970s (see Table 1). The process of "technophysio evolution" can be characterised as one of human emancipation from climatic constraints. However, the fact that human beings have gained increasing control over their environments during the last two hundred years does not mean that we can take this for granted over the next two hundred years.

Endnotes

[1] *Climate* refers to the average weather pattern in a place over a relatively long period of time, and *weather* to the mix of events that happen in the atmosphere during a short period of time. In this paper we are concerned with long-run changes in climate, and not on the impact of short-run events (such as storms or heat waves).

[2] The other components of the index included hypoplasias, anaemia, number of teeth, dental abscesses, infections and evidence of degenerative joint disease (Steckel et al. 2002, 69).

[3] We gathered data from 11 countries in total: China, England, France, Germany, Ghana, India, Indonesia, Mexiso, Poland, Spain and the United States.

[4] In this process, for example, we had to exclude data on African slaves from Eltis (1990) available for the early nineteenth century (see http://www.slavevoyages.org/ (accessed 7 May 2017)).

[5] We plan to examine data for the other countries in future research.

[6] The main area from which our data are taken stretches from Paris in the north to the Massif Central in the south, though we also have a substantial amount of data from Alsace-Lorraine. Modern records suggest that these areas have mean annual temperatures and precipitation close to the average for France as a whole. They also include a range of environments, including mountains in the Massif Central. We do, however, have a relative shortage of data from maritime France.

[7] The data derive from the ports of Kolkata (Calcutta) and Chennai (then known as Madras). Kolkata is in north-eastern India and most people using Kolkata came from Uttar Pradesh and Bihar, with some from Assam and West Bengal. Chennai is in south India and most people using Chennai came from the states of Tamil Nadu, Ketala, Karnataka and Andhra Pradesh. The largest contingent in our data set came from Uttar Pradesh.

[8] A similar trend is found in the northern and eastern states from which most of our data come, for example Massachusetts, New York and Pennsylvania (see https://www.ncdc.noaa.gov/temp-and-precip/state-temps/, accessed 25 April 2017).

[9] The Confederate Army sample, though drawn from the south, is very small relating to the Union Army sample.

[10] To address issues of heaping on height (the accuracy of the recorded height measurements) Fogel et al. (1983) showed that even with large amounts of heaping (in the range of 15-30%) the error will only be in the region of 0.254 centimetres or 0.1 inches.

[11] See http://www.ine.es/en/, accessed 11 April 2017.

[12] See Bodenhorn et al. (2017) and Komlos and A'Hearn (2016) for a recent debate about the causes of the mid nineteenth century decline in heights.

[13] See www.berkeleyearth.org/ accessed 11 April 2017.

[14] Because we have been working with transcribed datasets, rather than original manuscript records, we made some corrections for obvious mistakes in the typing process (for example, Jolotepec for Yolotepec in Mexico). Further work was needed to ascertain the present names of the locations since some places changed their names over time (Rājputāna for Rājasthān in India). We excluded individuals born in the jurisdictional domain of a country but geographically located far away from the country itself (such as the Canary Islands in the case of Spain) and, as we used the present borders of the countries, we excluded individuals who were born outside these (for example, Spanish recruits who were born in Spanish Morocco). Both these cases for removing observations have been recorded under the category of "foreign birth country" in Table 2.

[15] We controlled for emigration and excluded observations when the country of birth and measurement were different, these observations are recorded under the category of "foreign birth country" in Table 2.

[16] The creation of overlapping periods might create serial correlation. However, annual regressions showed similar results to windows of 15 years and since we restrict our estimation to the window, within the window the ordinary least squares assumptions hold.
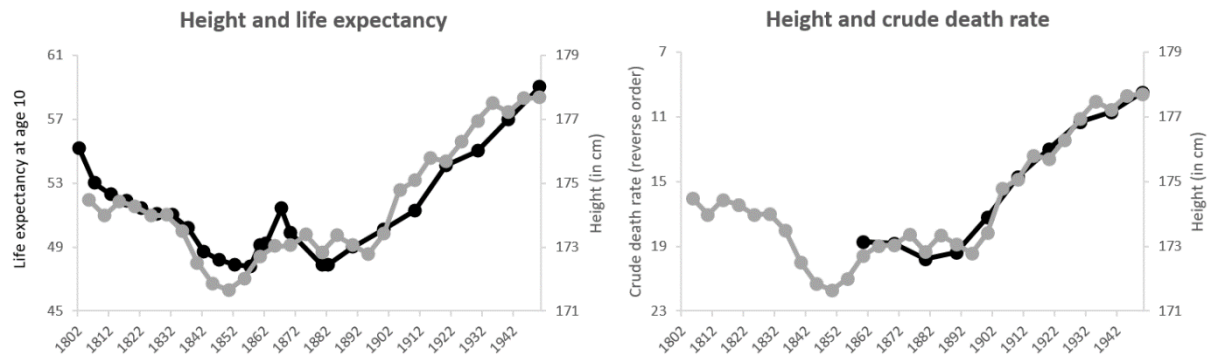
Appendix A1: Regional distribution of number of observations, temperature, rainfall and land cover and land use in France, India, Spain, Mexico and the United States.

Sources: For height data see text and Table 2, climatic data from Harris (2014) and land cover and land use systems from Channan et al. (2014). **Notes**: Data for temperature, rainfall and land cover and land use systems averaged for the period 1901-1910.
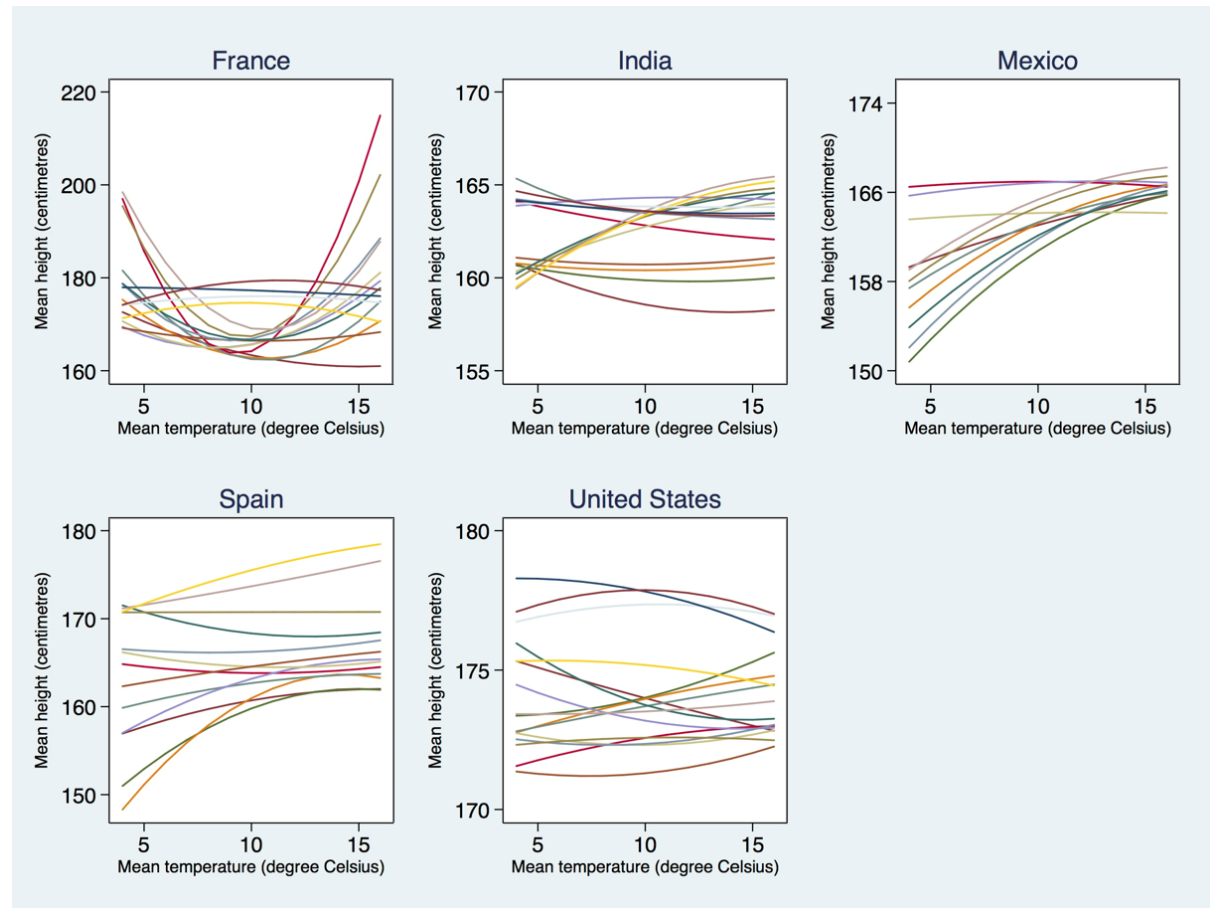
Appendix A2: Height series in the US and other general indicators of wellbeing

Notes: This figure compares our height series for the US with two other general indicators of health and wellbeing: the expectation of life at age 10 years and the crude death rate. They show a close correspondence. Average heights are measured in cm, life expectancy at age 10 in years and crude death rates at per thousand. **Source**: Crude death rates from Floud et al. The Changing Body (2011: 322, Tab. 6.8) and life expectancy at age 10 from Costa (2015) "Health and the Economy in the United States from 1750 to the Present" and also reported in Fogel, R. (1986), 'Nutrition and the decline in mortality since 1700: some preliminary findings', in S. Engerman and R. Gallman, eds., Long-term factors in American economic growth, Chicago: University of Chicago Press, 439-555.

Appendix A3: Non-linear impact of temperature on stature.

Notes: Each line shows the results of regressing individual heights on a linear and quadratic trend in temperature for each decade. As discussed in the text (end of Section 6) we assumed a linear relationship between climate and stature. However, since the relationship between climate and stature is not constant over time and across space we also estimated models by decade using a quadratic specification with the aim to see whether the departure from linear should be important. Results show that for all the countries apart from France, the quadratic modelling gives similar results to the linear assumption. Yet, in France for some decades the linear assumption seems poor. These decades are the 1820s to the 1850s. However, it should be noticed that we do not have much data in these years and the data may be heavily clustered (see the large standard errors in Figure 4). **Sources**: See text.

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