The economic impact of climate in the long run

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Abstract

Early scholars were convinced that geography is destiny, that climate determines the human condition. Current economists by and large argue that institutions are destiny, that the only thing that matters to humans are other human beings. Neither position is tenable. I review the literature and present new empirical evidence that shows that climate does have a significant effect on development, that this effect is mediated by institutions, and that the effect shrinks with affluence.

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1 Introduction

Poverty is concentrated in the tropics and subtropics. The correlation is clear, but causation is disputed. This matters, for if a warm climate prevents or slows economic development, then a warming climate would hurt economic growth. I assess the literature on climate and development, and present new empirical evidence.

The literature on climate and development is vast, spanning almost three millennia. I cannot present a comprehensive survey in a limited space. See Castells-Quintana *et al.* (2017) for an attempt. Instead, I highlight the two extreme positions, environmental determinism and institutional determinism, that dominate the earlier and later literature, respectively. I take an intermediate position, but one that is closer to institutionalism. The empirical evidence—both from the literature and new material presented below—supports that position: Climate matters, but is not dominant, it is mediated by institutions, and its impact weakens over time.

The paper continues as follows. Section 2 reviews the literature, focusing on patterns of development in 2.1, natural disasters in 2.2, and weather in 2.3. Section 3 presents new regression results, for population density in 3.1 and for per capita income in 3.2. Section 4 concludes.

2 Previous literature

2.1 Development

There are three schools of thought on the impact of geography and climate on human development: (*i*) climate is destiny; (*ii*) climate is important; and (*iii*) climate used to be important but is no longer.

Environmental determinism was a popular theory in centuries past. Zhong Guan (c780 BC) posits that water is the root from which beauty and ugliness, worthiness and unworthiness, stupidity and giftedness are produced. A people's character was determined by the rivers on whose shores they dwelt. Hippocrates (400 BC) argued that pronounced seasons cause savagery and courage, while weather that changes little breeds indolence and cowardice. Aristotle (350 BC) goes further, writing that "[t]hose who live in a cold climate and in Europe are full of spirit, but wanting in intelligence and skill [...] [w]hereas the natives of Asia are intelligent and inventive, but they are wanting in spirit, and therefore they are always in a state of subjection and slavery." Ibn Khaldun (1377) contradicts Aristotle, arguing that *heat* makes one merry and stupid, and cold air gloomy and overly concerned for the future. These sentiments lasted. Huntington (1915) claims that heat makes for lack of industry, an irascible temper, drunkenness and sexual indulgence.[1]

[1] Huntington (1917) even argues that climate change caused the collapse of the Roman Empire, a

Febvre (1922) was one of the first to argue against environmental determinism, emphasizing that social forces are at least as important. He of course had the benefit of hindsight against Aristotle's claim that Europeans would be incapable of ruling over others and Hippocrates' prediction that Europe would never have absolute monarchs. Environmental determinism is now often seen as an historical rather than a contemporary view (Lewthwaite, 2001), a view that is tainted by post-hoc justifications of the position of the hegemon (Blaut, 1999).[2] However, environmental determinism lives on. Jared Diamond (1998) is the main current proponent of this hypothesis. Diamond argues that the current distribution of income across the world can be explained by a few factors of geography. The orientation of the axis of the Eurasian continent is East-West. That implies that areas with similar climates are connected. An innovation in one place—say, a newly domestic animal or a newly bred crop—can be used in a large area. This is not the case on continents with a North–South orientation, that is, Africa and the Americas. The distribution of domesticable plants and animals is also supposed to have been more favourable in Eurasia. Europe got ahead of China because its geography was conducive to many small kingdoms, competing for supremacy and thus innovative; China's geography, instead, invited a uniform empire. Diamond's grasp of history is not without blemish, and his notion that human history is shaped by geographic factors beyond our control is in contrast with the facts. Diamond's hypothesis could be dismissed when comparing the two halves of Hispaniola and Korea. Nevertheless, Olsson and Hibbs (2005) find empirical support: Diamond's drivers do have explanatory power for the distribution of income.[3]

David Landes (1998) argues that its cool summers, mild winters, and regular rains gave Europe an advantage over other places. Others, including Jeffrey Sachs (2003, see also Gallup *et al.* (1999)), argue that climate and geography are contributing factors to (under)development, influential but not dominant. Diseases such as malaria and diarrhoea impair children's cognitive and physical development. This leads to poverty in their later life so that there are limited means to protect their own children against these diseases. Furthermore, high infant mortality may induce parents to have many children, and risk-averse parents to have more children than they really want. As a result, investment in the children's health and education is spread thin and the children are likely to grow up to a life of poverty. Infectious diseases are more virulent and prevalent in warmer and wetter climates. Unlike Diamond, Landes and Sachs are not determinists. Sachs indeed calls for active measures to suppress tropical diseases, not just to alleviate the immediate suffering but also to overcome the economic impact in the long run.

Infrastructure also affects economic development (Bougheas *et al.*, 1999; Fernald, 1999;

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theme picked up later by Harper (2017). The causal chains in Harper's book are long and fragile.

[2] Robert Rankin duly places the Garden of Eden in Brentford, London.

[3] Andersen *et al.* (2016) argue that it is not climate, but rather UV-radiation that explains incomes, through its impact on the probability of going blind and hence the incentive to learn a craft or trade. Their order of magnitude seems off.

Morrison and Schwartz, 1996; Röller and Waverman, 2001). Travel and transport allow for trade (Ricardian growth) and specialization (Smithian growth). Infrastructure is more expensive in some climates than in others, for example because of repairs after floods (Schweikert *et al.*, 2014). Disasters have other effects on development too. Savings' rates would be higher (Skidmore, 2001). Households and companies trade-off returns to investment against its safety. In a high-risk environment, safe assets with a low return would be preferred, particularly if insurance or asset diversification is expensive or unavailable—as is often the case in poor countries (Bénabou, 1996). Slow growth is the result.

Some have argued that highly volatile environments induce a feast-and-famine culture. A rational response to the risk of losing it all, whether to a drought or a warlord, could indeed be to enjoy the good times while they last and hope to make it through the bad times. If such an investment-is-pointless attitude becomes ingrained, people may be slow to escape poverty even if volatility falls (Filipski *et al.*, 2019). van de Vliert (2008) documents many other examples of how climate may have affected culture.

Others, including Acemoglu *et al.* (2001, 2002), taken a different position: Climate used to matter, but no longer. They argue that climate and geography were important in the past in shaping institutions (education, rule of law, etc.) but that institutions explain the current pattern of development. Tropical diseases determined the pattern of European colonization. Some parts of the world were hospitable to Europeans, who settled there (often after removing or killing the natives) and established universities, courts and representative government. Europeans could not cope with the diseases prevalent in other parts of the world, and therefore raided rather than settled. The plunder, pillage and rape that followed destroyed native societies. This historical divide, which is due to climate through the spread of tropical diseases, explains the current income distribution rather well. Alsan (2015) argues that the tse-tse fly, which is confined to certain climates, plays an important role in Africa's poverty, as it prevents the use of animals for milk, meat, transport and traction, and indirectly leads to more political fragmentation, which in turn hampered economic growth.

Easterly and Levine (2003) and Rodrik *et al.* (2004) agree that institutions are the only thing that matters *now*: Climate and geography have no power to explain the current distribution of income across the nations of the world once the effects of education, the rule of law, the quality of governance have been accounted for. They also find that climate does explain the strength of institutions.

This extreme position—that the only thing that nowadays matters to humans are other humans—cannot seriously be maintained. Climate indisputably affects agriculture, energy, health, and tourism. Geography incontrovertibly affects transport. Nordhaus (2006) and Henderson *et al.* (2018) use subnational rather than national data. Climate matters in their analyses, but as they do not control for institutional variables, instead relying on country fixed effects, they do not refute the earlier findings of Acemoglu, Easterly, and Rodrik.

All three schools of thought—climate is destiny, climate is important, climate was important but is no longer—have empirical support. See Table 1. This reflects the difficulty of establishing causality in a cross-section when there are many confounding factors—including, to confuse the institutional determinists, evidence that climate shapes culture.

Unfortunately, the current state of knowledge is that we do not know. I think we can safely exclude the two extreme positions, but it is too early to say whether climate played in minor or major role in determining why some people are poor and others rich—and hence under what circumstances climate change would prevent certain economies from growing.

If climate is a contributing factor to the probability that people are trapped in poverty, the impacts of climate change may be (much) larger than commonly believed (Tol, 2018). The welfare impacts of growing at a small rate versus not growing at all are large when compounded over a century or more.

2.2 Natural disasters

Natural disasters have a number of effects on the economy (Albala-Bertrand, 1993). When disaster strikes, economic activity is disrupted and input factors are destroyed. Some disasters, such as floods and storms, particularly affect physical capital, such as buildings, roads and bridges. Other disasters, such as epidemics, primarily affect people and thus the labour force. After the disaster, there is recovery. The deaths are buried, debris cleared away. Savings are mobilized, and insurance payouts and charity received to rebuild houses and roads. These are economic activities, and thus contribute to Gross Domestic Product (GDP). Natural disasters thus neatly illustrate the *broken window fallacy* of Bastiat (1850): Destruction of the capital stock is not measured by GDP (but rather by Net Domestic Product). Repair of the capital stock is. A naive look at GDP growth rates may thus lead one to conclude that natural disasters are good for short-term economic growth. This is not the case. Natural disasters stimulate economic activity. Natural disasters do not improve welfare. GDP is a measure of economic activity. It is not a welfare indicator. In cases like these, we should focus on NDP growth rates, but data availability is limited.

Natural disasters have different impacts at different phases of the business cycle (Tol and Leek, 1998). During a recession, the loss of input factors is less problematic as there is overcapacity anyway. The recovery phase is a Keynesian economic stimulus. During a boom, capacity is tight and lost inputs cannot readily be replaced. The demand stimulus from recovery may drive up inflation rather than output. Recovery replaces destroyed capital goods with new ones. Although the initial response is often to restore things

Table 1: Empirical evidence of the impact of climate on economic development and growth

Study	Data	Dependent variable	Findings
Gallup *et al.* (1999)	Cross-section	Per capita income growth	A climate suitable for malaria affects development and growth; controlled for institutions.
Acemoglu *et al.* (2001)	Cross-section	Per capita income	Protection against the risk of expropriation is the key predictor of development. Expropriation risk is best explained by the mortality of European settlers at the onset of colonialization.
Bloom *et al.* (2003)	Cross-section	Per capita income	Development in poor countries, and the chance of being poor are affected by temperature and precipitation.
Easterly and Levine (2003)	Cross-section	Per capita income	Geography and climate explain a broad range of institutions. Institutions in turn explain development.
Rodrik *et al.* (2004)	Cross-section	Per capita income	Geography and climate explain a broad range of institutions. Institutions in turn explain development.
Olsson and Hibbs (2005)	Cross-section	Per capita income	Climate, latitude, continental size and orientation, and domesticable plants and animals significantly influence development; controlled for institutions.
Nordhaus (2006)	Cross-section	Income	The relationship between temperature and output is negative when measured per capita and positive per area.
Barrios *et al.* (2010)	Panel	Growth	The secular decline in rainfall in sub-Saharan Africa explains slow economic growth.
Dell *et al.* (2012)	Panel	Growth	Temperature shocks affect economic growth, but only in poor countries.
Alsan (2015)	Cross-section	Night lights, number of cattle	Climate limits the spread of the tse-tse fly, which affected pre-colonial agriculture and political centralization, and hence current development.
Andersen *et al.* (2016)	Cross-section	Per capita income	Not climate but ultraviolet radiation explains disease ecology and hence development.
Henderson *et al.* (2018)	Cross-section	Night lights	Temperature, rainfall, growing days and malaria suitability all affect development.

exactly as they were, in fact replacements are often superior: New machinery would be state-of-the-art, new buildings better designed, new roads without previous bottlenecks, and so on. This does not accelerate economic growth in the long run: The capital stock would be replaced anyway. Natural disasters force the hand of economic agents with regard to the timing of replacement investment. Discretionary timing would be preferred.

The impact of natural disasters on the economy in the short term is therefore mixed, but probably negative on net. The same is true in the long term. If there is a risk of natural disasters, resources are diverted to protective measures, be they financial (e.g., insurance) or physical (e.g., dykes). Insurance premiums are invested in liquid assets with a low return. The return on dykes is essentially zero. If the disaster risk were zero, those resources could be used for consumption or for investment in productive assets.

Natural disasters have different impacts on different economies (Cavallo and Noy, 2011; Kellenberg and Mobarak, 2011). Recovery requires resources. In developed economies, recovery is paid for by insurance, from household and company reserves, by the government, or by new loans from commercial lenders. In developing economies, contributions from these sources are limited, and recovery depends on support from informal networks and charity. Recovery from natural disasters is therefore slower, and sometimes much slower in developing countries than in developed economies. There may be hysteresis if customers switch to new suppliers.

The empirical evidence on the impact of natural disasters has grown rapidly, revealing heterogeneity in many dimensions. See Table 2. Earlier studies used the EM-DAT data,[4] which only reports natural disasters when they cause substantial damage to humans.[5] This compounds the endogeneity of richer societies being better able to shield themselves from natural disasters. There is now a substantial body of literature that shows that natural disasters indeed slow down economic growth (Klomp, 2014; Lazzaroni and van Bergeijk, 2014). This negative effect is stronger in poorer countries, probably because of financial underdevelopment, which may itself be caused by natural disasters (Keerthiratne and Tol, 2017; Klomp, 2014, 2015, 2017, 2018, 2020; McDermott *et al.*, 2013). That is, natural disasters slow economic growth and more so in poorer countries. In other words, areas which are more prone to extreme weather are more likely to be trapped in poverty.

[4]See `https://public.emdat.be/`.

[5]The data by Felbermayr and Gröschl (2013) does not suffer this problem. See `https://www.ifo.de/en/ebdc-data/ifo-game`.

Table 2: Studies of vulnerability to natural disasters.

study	hazard	region	explanatory variables
Yohe and Tol (2002)	natural disasters	world	poverty (+), inequality (+), population density (+)
Kahn (2005)	natural disasters	world	poverty (+), democracy (-), institutions (-)
Toya and Skidmore (2007)	natural disasters	world	poverty (+), institutions (-)
Escaleras *et al.* (2007)	earthquakes	world	corruption (+)
Kellenberg and Mobarak (2008)	natural disasters	world	poverty (- then +)
Price (2008)	hurricanes	USA	poverty (+), black (+)
Raschky (2008)	natural disasters	world	poverty (- then +), institutions (-)
Zhang *et al.* (2009)	drought	China	poverty (+)
Yamamura (2010)	natural disasters	Japan	poverty (+), social capital (-)
Keefer *et al.* (2011)	earthquakes	world	poverty (+), democracy (-)
Escaleras and Register (2012)	natural disasters	world	decentralization (-)
Hu *et al.* (2012)	earthquakes	China	poverty (+)
Rubin and Rossing (2012)	natural disasters	Latin America	poverty (+), inequality (+)
Wamsler *et al.* (2012)	natural disasters	Brazil, El Salvador	education (-)
Ward and Shively (2012)	natural disasters	world	poverty (+)
Yamamura (2012)	natural disasters	world	ethnic polarization (+)
Chen *et al.* (2013)	natural disasters	China	poverty (+)
Ferreira *et al.* (2013)	floods	world	poverty (+), institutions (?)
Ji and Ying (2013)	natural disasters	world	poverty (+), medical services (-)
Padli *et al.* (2013)	natural disasters	world	poverty (+), education (-)
Skidmore and Toya (2013)	natural disasters	world	decentralization (-)
Fankhauser and McDermott (2014)	hurricanes, floods	world	poverty (+), institutions (?)
Felbermayr and Gröschl (2014)	natural disasters	world	poverty (?), institutions (+), trade (+)
Huang (2014)	floods	China, Japan	poverty (- then +)
Iwata *et al.* (2014)	natural disasters	Japan	institutions (+)
Muttarak and Lutz (2014)	natural disasters	case studies	education (-)
Rubin (2014)	natural disasters	Vietnam	poverty (+), inequality (+)
Zhang *et al.* (2014)	natural disasters	China	poverty (+)
Zhou *et al.* (2014)	natural disasters	China	poverty (+), education (-), young (+), old (+)
Jongman *et al.* (2015)	floods	world	poverty (+)
Lim *et al.* (2015)	heat waves	East Asia	poverty (+)
Lin *et al.* (2015)	earthquakes	Taiwan	poverty (+), female (+), young (+), old (+)
Lin (2015)	natural disasters	world	democracy (-), institutions (-)
Park *et al.* (2015)	hurricanes	South Korea	poverty (+), building codes (-)
Toya and Skidmore (2015)	natural disasters	world	ICT (-)

Wen and Chang (2015)	natural disasters	world	right-wing government (-)
Austin and McKinney (2016)	natural disasters	world	poverty (+), democracy (-), women's rights (-)
Breckner *et al.* (2016)	natural disasters	world	insurance (-), institutions (-)
Dresser *et al.* (2016)	hurricanes	Atlantic	poverty (+)
Escaleras and Register (2016)	natural disasters	world	corruption (+)[6]
Klomp (2016)	natural disasters	world	poverty (+)
Peregrine (2017)	natural disasters	ancient societies	democracy (-)
Persson and Povitkina (2017)	natural disasters	world	democracy (-), institutions (-)
Tselios and Tompkins (2017)	natural disasters	world	decentralization (+)
Villagra and Quintana (2017)	tsunami	Chile	institutions (-)
Ward and Shively (2017)	natural disasters	world	poverty (+)
Zuo *et al.* (2017)	natural disasters	world	institutions (-)
Albuquerque Sant'Anna (2018)	floods	Rio de Janeiro	urban infrastructure (-)
Enia (2018)	natural disasters	world	rule of law (-)
Hu *et al.* (2018)	floods	world	population density (+), poverty (+)
Liu *et al.* (2018)	earthquakes	China	public infrastructure (-), insurance (-)
Peregrine (2018)	natural disasters	ancient societies	democracy (-)
Winsemius *et al.* (2018)	floods and droughts	world	poverty (+)
Wu *et al.* (2018)	natural disasters	China	poverty (+)
Yonson *et al.* (2018)	hurricanes	Philippines	poverty (+), institutions (-), urbanization (+)
Formetta and Feyen (2019)	natural disasters	world	wealth (-)

[6] Escaleras and Register further find that natural disasters increase corruption.

2.3 The impact of weather on the economy

Natural disasters apart, there is a recent and increasing interest in studying the economic impact of weather (see Dell *et al.*, 2014, for an early review). Many of these studies are cast as relevant to climate change, but that is a bit of a stretch. Deryugina and Hsiang (2017) set out the conditions under which a weather impact equals a climate impact. These conditions are rather strict. Lemoine (2018) adds rational expectations. If these conditions are not met, a weather impact is to a climate impact as a short-term elasticity is to a long-term elasticity: Perhaps an upper bound.

This is even more so for the impact of weather on development in the long-term. Weather extremes may well preclude certain options—a small chance of frost puts an end to non-hardy perennials, for instance. But weather extremes are part of climate. You need hysteresis for weather to matter in the long-run. Had the sun not shone that day, this country would have been much poorer. Such an argument can be made for certain aspects of political and military history, but it is much harder to maintain for economic development.

Dell *et al.* (2012) show that temperature affects economic growth, and more so in poorer countries. Burke *et al.* (2015) also finds that temperature affects economics, and more so in hotter countries. Testing Dell's hypothesis against Burke's, Letta and Tol (2018) find in favour of Dell.[7] This cannot explain the correlation between climate and development, but it does again suggest path dependence and poverty traps. Countries that had the good fortune of a long sequence of mild weather became less vulnerable to the bad weather that inevitably followed. Barrios *et al.* (2010) find that the seminal drying of Sub-Saharan Africa largely explains its lacklustre economic growth in the second half of the 20th century.

3 New evidence

3.1 Climate in the age of Malthus

Thomas R. Malthus (1798) is one of the fathers of environmentalism, noting that a geometric increase in population combined with an arithmetic increase in food supply would lead to famine. His ideas have echoed through the ages, most prominently in the 20th century in the works of the Club of Rome (Meadows *et al.*, 1972) and, more recently, in the activism of Extinction Rebellion (Westwell and Bunting, 2020).

Malthus is also one of the great Classical economists. The modern incarnation of his theory of economic development is that technological progress is not used to improve living standards, but rather to increase population growth so that more people live at sub-

[7]These studies find no impact of rainfall. Damania *et al.* (2020) shows that rainfall does have an effect on subnational economic growth rates.

sistence level (Eckstein *et al.*, 1988). While usually considered as a model that describes changes over time, it can be applied over space as well: In a Malthusian equilibrium, areas with better technologies are more densely populated.

The standard Malthusian model is limited to fertility and mortality. Boustan *et al.* (2020) shows that, for the USA between 1920 and 2010, natural disasters led people to leave the affected area, echoing an earlier finding by Strobl (2011). If these results are representative, migration thus reinforces the Malthusian model, with high (low) population densities in (un)favourable areas.

Kees Klein Goldewijk *et al.* (2010) have estimated human population densities for the whole world, at a $5' \times 5'$ grid, for the last 12,000 years.[8] I regress the natural logarithm of population density on the current climate to discern its influence on spatial differences in technology, as follows

$$\ln D_{i,j,t} = \alpha_{0,t} + \alpha_{1,t}T_{i,j,t} + \alpha_{2,t}T^2_{i,j,t} + \alpha_{3,t}P_{i,j,t} + \alpha_{4,t}P^2_{i,j,t} + \alpha_{5,t}T_{i,j,t}P_{i,j,t} + \alpha_{6,t}\ln D_{i,j,t-1} + u_{i,j,t} \quad (1)$$

where $D_{i,j,t}$ is population density for latitude i, longitude j, and time t, $T_{i,j}$ is temperature, $P_{i,j}$ is precipitation, and $u_{i,j}$ are IID errors. Observations are for 10,000BC, 9,000BC, ..., 0AD, 100AD, ... 2,000AD. For the oldest observations, the lagged dependent variable is omitted.

There are many observations. In 10,000BC, 228,563 grid cells were occupied by humans, increasing to 277,987 grid cells in 2000. It is therefore no surprise that the estimated coefficients are highly significant.

Figure 1 summarizes the results. It shows the temperature and rainfall for which population density would be highest if climate were the only thing that mattered:

$$P^*_t = \frac{2\alpha_3\alpha_2 - \alpha_1\alpha_5}{4\alpha_3\alpha_2 - \alpha_5^2} \quad (2)$$

$$T^*_t = -\frac{\alpha_1 + \alpha_5 P^*_t}{2\alpha_{2,t}} \quad (3)$$

The 90% confidence intervals in Figure 1 were derived by simulating 10,000 draws for the parameter estimates.

Figure 1 shows that the area with the highest potential population density in 10,000BC had a temperature of 23°C and 3,000 mm/year rainfall. Early humans liked it warm and wet. With primitive heating and clothing, cold winters were deadly. High net primary production in the tropics meant abundant food.

For later years, the interpretation of the numbers in Figure 1 changes, as we condition on population density in the previous period. From 9,000BC to 3,000BC, population

[8] See `https://themasites.pbl.nl/tridion/en/themasites/hyde/`.

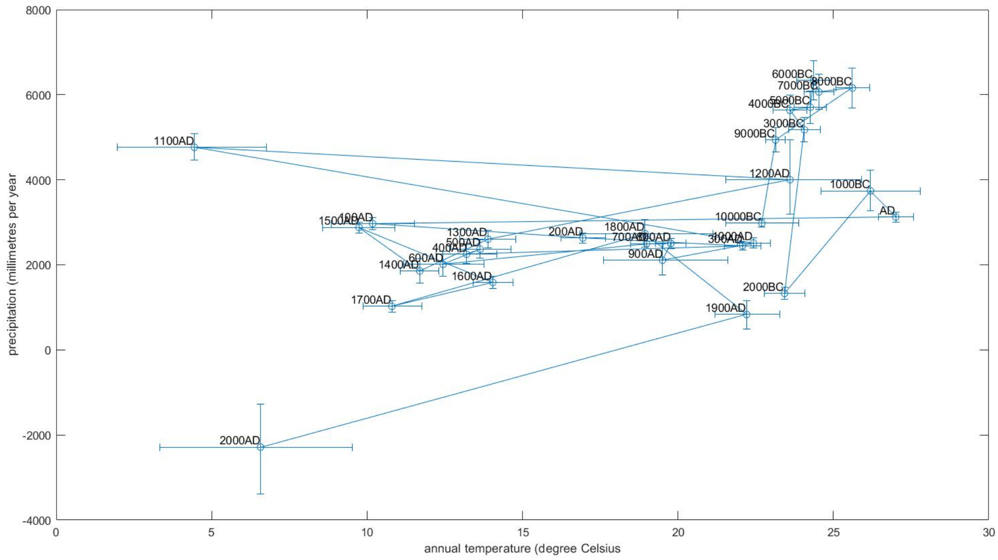

Figure 1: Highest potential population density by annual rainfall and temperature over time.

density grew fastest in areas that are hot and wet. The optimum climate is close to the hottest (30°C) and wettest (8,000 mm/year) places in the sample.

In 2000BC, we see a marked shift towards dryer conditions, presumably as irrigation improves. In 100AD, we observe a large push towards temperate climates. In the centuries that follow, the optimal temperature for population growth shifts around a lot while the best precipitation stays in a narrower range. 1100AD stands out with rapid population growth in Scandinavia. In the 19th century, we observe human colonisation of the drylands. This continues in the 20th century, when also Siberia and Canada are populated.

The key insight of Figure 1 is that, over time, the link between climate and human life weakened. This is highlighted in Figure 2, which shows the adjusted R^2 and the Wald statistic for joint significance of the climate parameters, two measures of the explanatory power of temperature and precipitation. As agriculture, irrigation, clothing, heating and cooling improved, humans moved into hitherto inhospitable areas. We now have bustling cities in the rainforest, the desert, and the Arctic—while humans continue to dream of moving to even more hostile places, such as Mars.

Xu *et al.* (2020) study the same data, arguing that human life is fragile to climate change. Their estimate of the human climate envelope is unfortunately biased, since they top-censored the data, did not correct their estimates for censoring, and extrapolate into the censored part of the data domain.

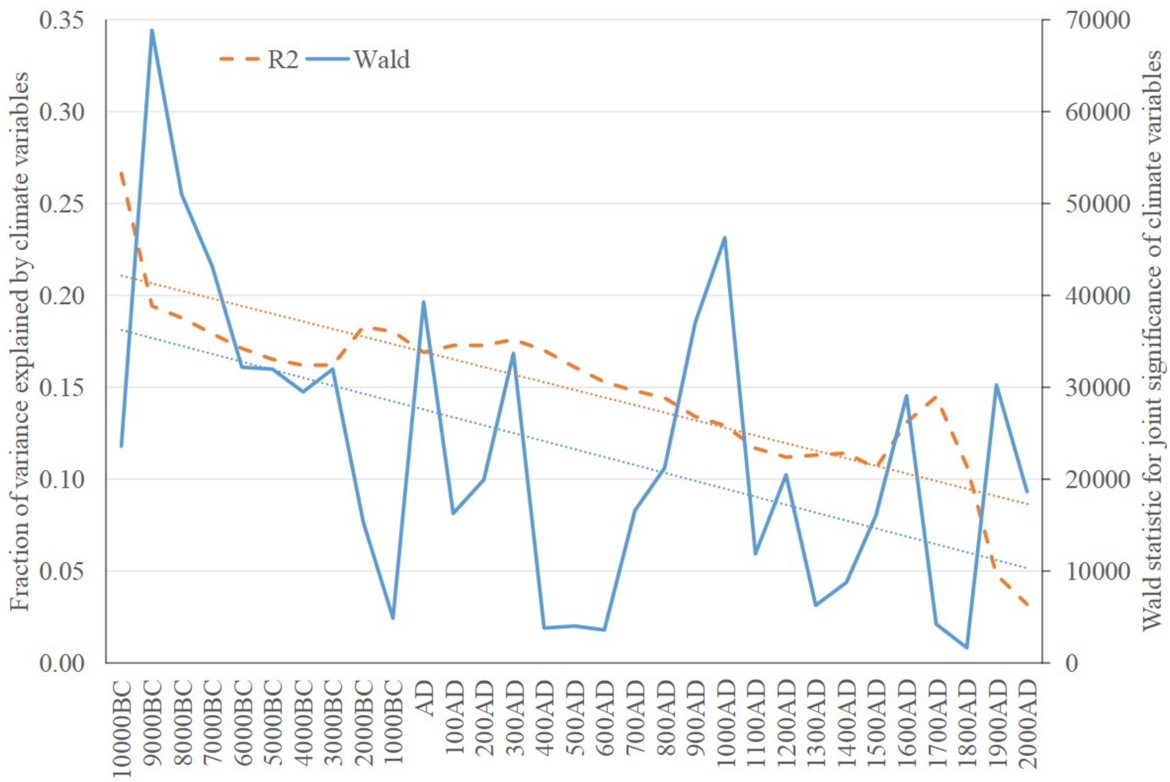

Figure 2: The explanatory power of climate for population density.

3.2 Climate in the age of Solow

Angus Maddison (2010) has gathered reconstructions of income in the past.[9] I use a regression identical to Equation (1), with the log of population density replaced by the log of per capita income, and grids replaced by countries. I do so for the years 1820, 1850, 1870, 1890, 1900, 1910, 1913, 1929, 1938, 1950, 1960, ..., 2010. Before 1950, the temporal spacing is determined by data availability. After 1950, in order not to overwhelm the analysis with recent data, I kept roughly the same frequency of observation.

The quadratic terms of temperature and precipitation are never significant. For 1820, the linear terms for temperature (0.29 (0.02) ln($/person/year)/Kelvin)) and precipitation (0.0079 (0.0005) ln($/person/year)/(mm/year)) are highly significant as is the cross-term (-0.00033 (0.00005) ln($/person/year)/Kelvin/(mm/year)). Together, these coefficients imply that, if annual rainfall exceeds 905 (77) mm/year, colder is better; in dryer places, hotter is better. If the temperature exceeds 23.9 (2.0) °C, dryer is better; in cooler places, wetter is better.

However, in later years, only the lagged dependent variable is significant, with the exception of 1990 (wetter countries are richer) and 2000 (wetter, hotter countries are richer). Those results disappear again in 2010. However, without the lagged dependent variable, temperature and rainfall and their interaction are always highly significant.

[9]See `https://www.rug.nl/ggdc/historicaldevelopment/maddison/`.

This analysis thus confirms the earlier findings Acemoglu *et al.* (2001), Easterly and Levine (2003), and Rodrik *et al.* (2004). Climate appears to have a significant effect on development, until you control for confounding factors. Climate may have a significant impact on those confounding factors, in which case climate may have had a significant impact on development in the past. Then again, that past impact may be apparent for lack of proper controls in the past.

Galor and Weil (2000) unify models of Malthusian stagnation and Solowian growth; see also Galor (2005, 2011). Dalgaard and Strulik (2013) show that these demo-economic models can be simplified to history-augmented Solow models. The augmentation is the time that has passed since take-off. They use this model to successfully explain the income distribution in the year 2000: Countries where the demographic transition started later are significantly poorer. They control for climate—tropical countries are significantly poorer—but do not test where climate is correlated with the start year of the fertility decline.

Figure 3 does that, plotting the year of the start of demographic transition according to Reher (2004) against the average temperature. There is clear correlation. Colder countries saw fertility fall earlier. For every degree warmer, the demographic transition is postponed by 2.18 (0.26) years. However, Figure 3 also shows that the correlation is far from perfect—other factors than temperature are important too. $R^2 = 0.34$ We cannot learn much from a relatively small cross-section.

Brückner and Ciccone (2011, see also Cáceres and Malone (2015)) find that, in the second half of the 20th century, rainfall shocks affect democratization in Subsaharan Africa. This matters, because democracy does cause growth (Acemoglu *et al.*, 2019). Figure 4 plots the year of the start of democracy, here defined as the year in which the Polity IV indicator turns positive,[10] against the average temperature. There is a positive correlation. Colder countries have been democracies for longer. One degree warmer means that democracy is delayed by 1.57 (0.50) years. However, the relationship is weak. $R^2 = 0.34$ And, of course, a small cross-section cannot teach us much.

3.3 Subnational data

The Global Data Lab has put together a data set of per capita income at the subnational level. Figure 5 plots this against the average temperature for the period 1981-2010. There is a clear correlation. For every increase in the temperature by 1°C, the natural logarithm of per capita income falls by 0.0921 (0.0029); this is the naïve prediction shown in Figure 5. If we control for non-climatic influences by introducing country dummies, the impact of temperature falls to 0.0118 (0.0026). That is, warmer regions within countries are statistically significantly poorer than the country average. The effect is small, 1.2% per

[10]See `https://www.systemicpeace.org/inscrdata.html`.

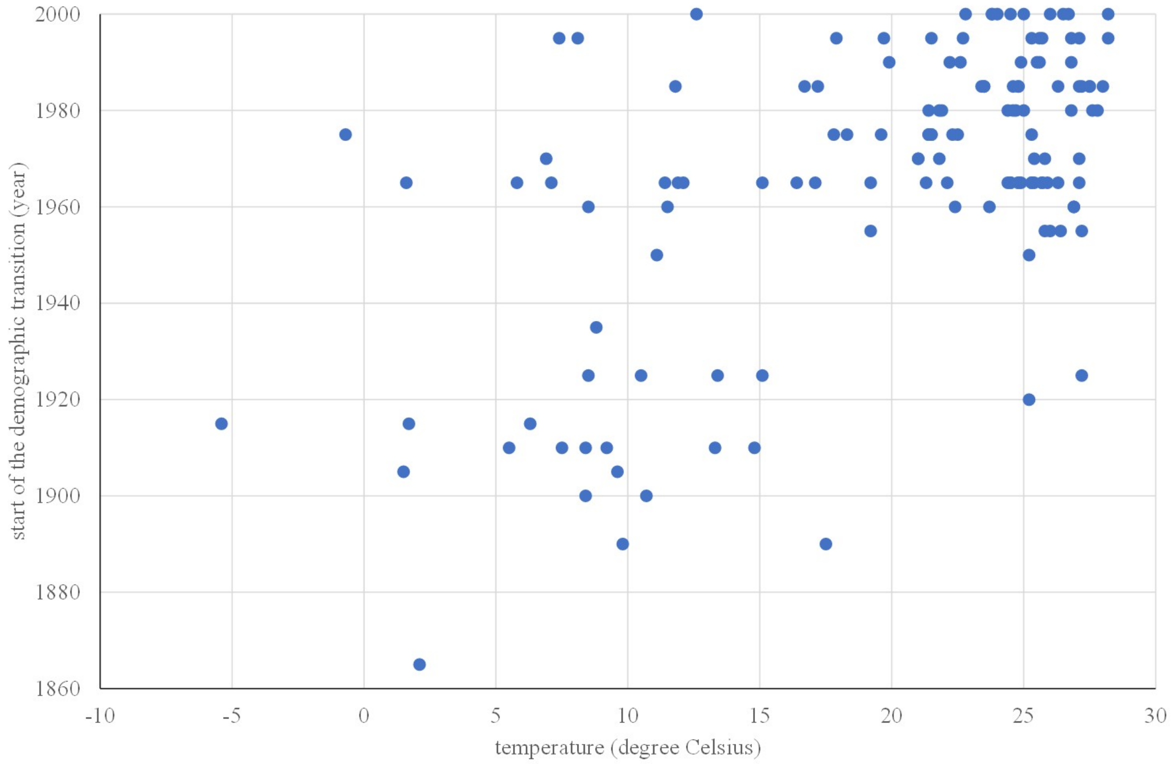

Figure 3: The start year of the demographic transition as a function of the average annual temperature.

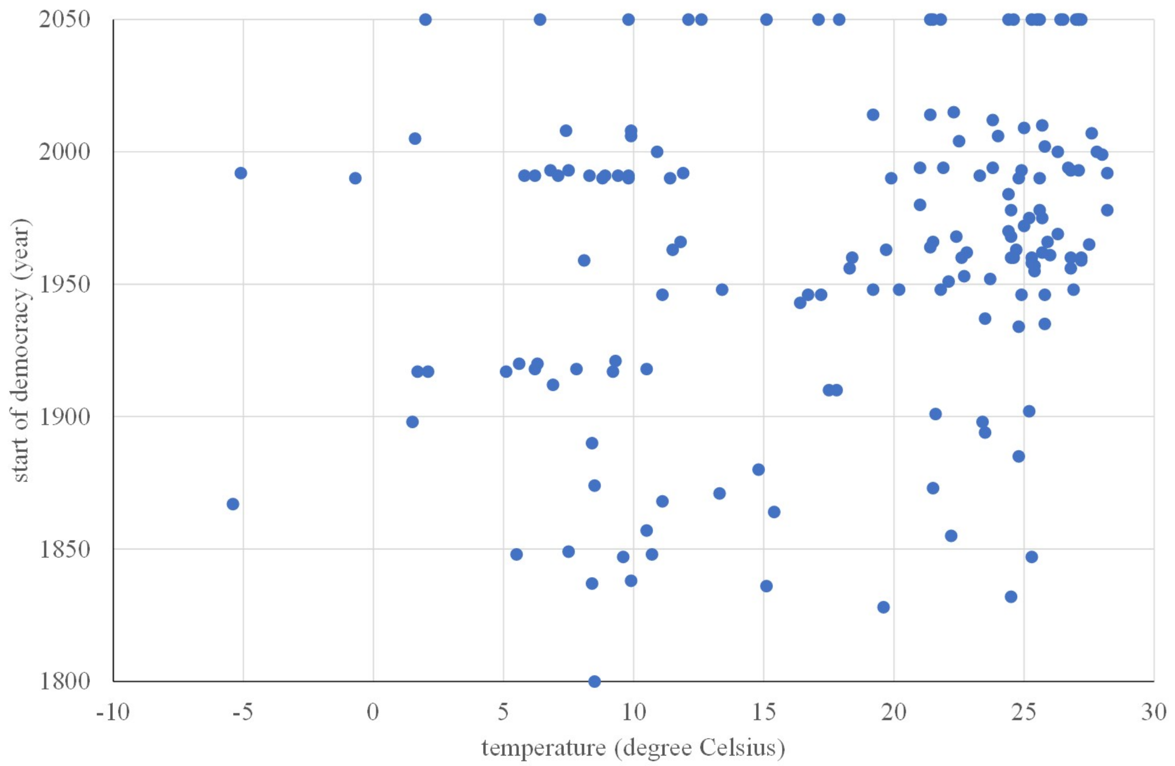

Figure 4: The start year of democracy as a function of the average annual temperature.

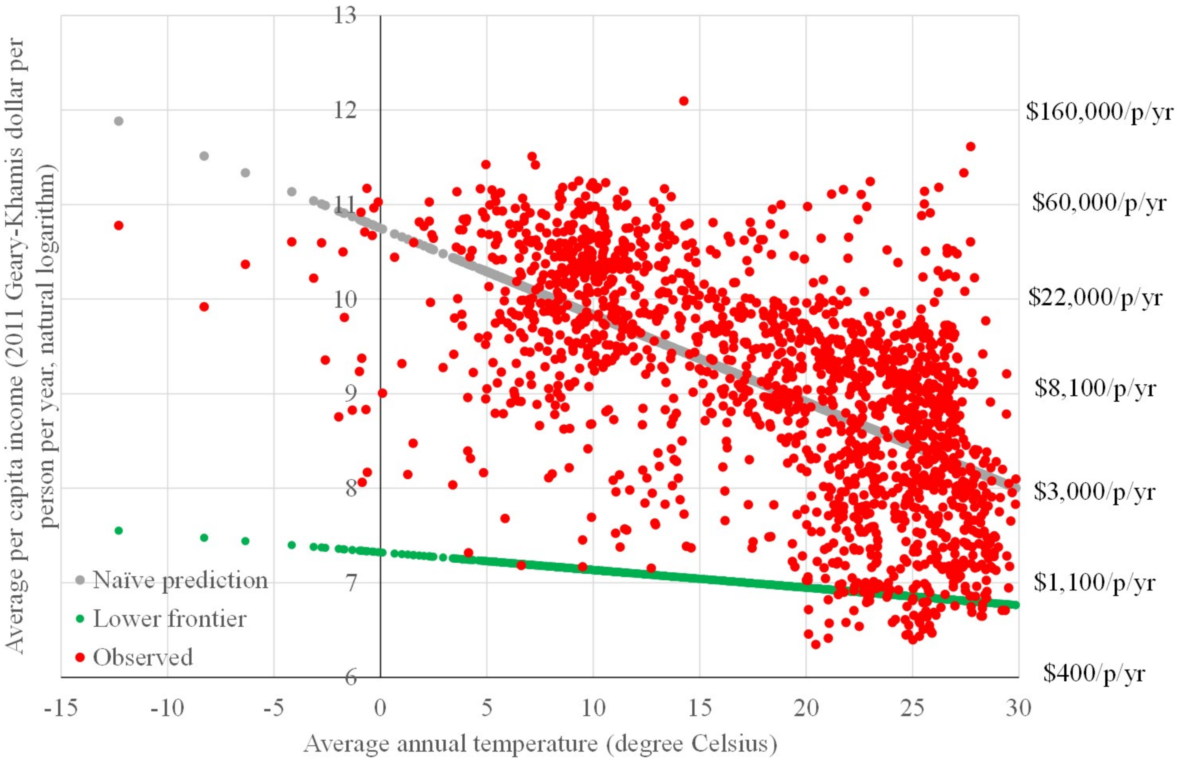

Figure 5: Per capita income at the subnational level as a function of the average annual temperature.

Kelvin.

Figure 5 shows something else too. In cold and cool places, no region is poor. In warm and hot places, some regions are rich but most regions are poor. I therefore estimated a stochastic frontier. When controlling for country dummies, temperature has no statistically significant effect on the maximum attainable per capita income, but hotter countries are likely to fall further below the frontier. Reversing the sign, I also estimated the lower bound. This is shown in Figure 5. The minimum attainable per capita income increases by 1.87% (0.32) per Kelvin. The floor placed under income is a weak one, ranging from $850/person/year in the hottest countries to $1900/p/yr in the coldest. Efficiency increases with temperature: Hotter countries can be further away from the lower bound than colder countries.

Figure 5 is consistent with the box-plots shown by Nordhaus (2006). Nordhaus' data is economic output, rather than income, per grid cell, rather than administrative unit. Nordhaus' data also reveal that affluence can be found anywhere, regardless of climate, while absolute poverty is absent in temperate climates.

4 Conclusion

For many centuries, environmental determinism was the majority view. Climate and geography are destiny. The then-dominant economic and military power was in the leading position because (the) God(s) had granted them the most favourable environment. This view prevails in a minority of analysts. In recent years, institutional determinism had the upper hand. The only thing that matters to people are other people. Climate and geography may have been important in the past but are no longer. There is a third school of thought who argue that climate and geography are influential but not dominant. Natural disasters and infectious diseases are both a cause and consequence of underdevelopment. Analysis of human population density over the last 12,000 years reveals a weakening effect of temperature and precipitation, and a persistence of population in place. Analysis of the national average per capita income over the last 200 years reveals a climate impact in 1820, but not later, although persistence is strong. Colder regions may have started growing their economies earlier. Analysis of regional per capita income reveals that temperature hardly limits wealth, but cold limits poverty.

These findings need to be revisited as finer-grained data becomes available for recent years and as historical observations come online. While it is unlikely that the main thrust of the current research will be overturned—there are too many studies already, with different methods applied to different data—new research should shed light on how and to what extent climate affects economic activity and human well-being, and how institutions and technologies mediate and shape these effects and in turn are shaped by climate. The existence, or not, of climate-related poverty traps requires particular attention, both because it is methodologically challenging and because it matters most to the people affected. As climate is projected to change, it is particularly important to investigate how policy interventions can help to alleviate the negative impacts of climate change and enhance its positive impacts.

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