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Climate Change in Developing Countries: Global Warming Effects, Transmission Channels and Adaptation Policies

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ABSTRACT

Using panel data covering 126 low- and middle-income countries over 1960-2017, we find that sustained positive temperature deviations from their historical norms have a non-linear negative effect on economic growth and growth per capita. A sustained 1°C temperature increase lowers real GDP per capita annual growth by 0.74–1.52 percentage points, irrespective of levels of development. We also find that temperature rise affects the households' intertemporal trade-off between consumption and investment, since the share of private consumption in total value-added increases while the share of investment declines. A sectoral decomposition shows that the share of industrial value-added also declines. While the share of agricultural value-added increases, agricultural output and productivity declines. Taken together, our results suggest that global warming will reinforce development traps, hindering further adaptation to climate change, particularly in the countries with the lowest levels of income given their lower resilience and higher socioeconomic vulnerability.

Keywords: Climate Change, Economic Growth, Adaptation, Developing Countries

JEL classification: C33, E20, O11, O13, Q54.

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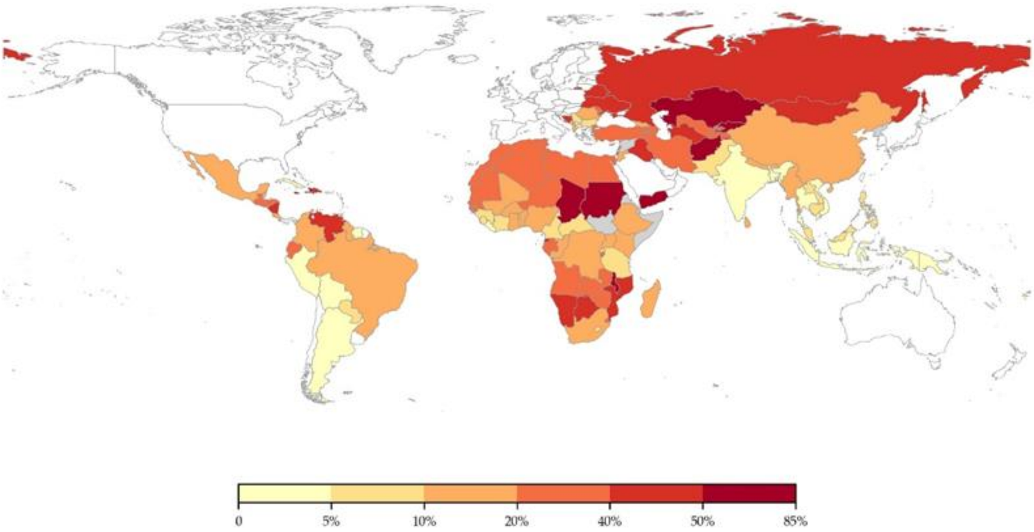
Non-Technical Summary

Climate change is one of the global challenges of our time. Its growing and global environmental and socio-economic impacts weigh significantly on the current international agenda and on national policymaking. Its impact may however vary significantly according to the level of economic development, with low- and middle-income countries bearing a disproportionate cost as they are affected by more rapid pace of climate change, including temperature rise, even though they have contributed only marginally to global carbon flows and stocks. They must therefore make substantial adaptation efforts, while contributing to mitigation, which may imply different priorities between mitigation and adaptation policies, in particular using policy toolkits that favor rapid economic growth. This is to ensure economic convergence with developed countries and help reaching Sustainable Development Goals. These policy dilemmas and the risk of collective action failures arising from differences in development levels were recognized by the 2015 Paris Climate Agreement, which includes annual transfer commitments from advanced economies to developing countries amounting to 100 billion US dollars.

Real GDP per Capita Loss due to Global Warming (1960–2017)



Note: Countries in gray have missing data, countries in white are not included in the sample. The figure indicates the cumulative loss in real GDP per capita in 2017 with respect to a counterfactual scenario characterized by mean annual temperatures equal to the historical norm (1900–1950).

The recent and rapidly growing literature that links temperatures and precipitations to output growth already points to a negative effect on economic growth in the vast majority of both developed and developing countries (Dell et al., 2012, 2014, Acevedo et al., 2020, Kahn et al., 2019), with possible accelerating and cumulative non-linear effects (Burke et al., 2015b). Because of the distinct characteristics of developing countries (higher demographic growth, lower levels of development and resilience, lower institutional quality), the impact of climate on economic growth (or development, proxied by GDP per capita) may however differ from that in high-income countries both in terms of scope and transmission mechanisms.

Using panel data of 126 low- and middle-income countries over 1960-2017, we find that sustained positive temperature deviations from their historical norms have a negative effect on economic growth and growth per capita, and that this effect is non-linear and accelerates as temperatures rise. A sustained 1°C temperature increase lowers real GDP per capita annual growth by 0.74 to 1.52 percentage points, irrespective of levels of development.

We also find that global warming increases the relative share of private consumption at the expense of investment, possibly reflecting more binding subsistence requirements in a context of declining output and potential output, leading to increased development gaps. The share of the agricultural value-added in GDP increases at the expense of industrial value-added, despite a decline in agricultural output growth, leading to a potential reinforcement of the "food problem": lower income countries need to dedicate a higher share of their resources to food production in order to meet their subsistence requirements. Both the sectoral and the demand decomposition of GDP indicate a shift towards short-term gains at the cost of economic diversification and future prosperity.

Global warming constitutes a development trap that threatens the gains in living standards, particularly since the beginning of the 21st Century. It requires even greater adaptation efforts in developing countries, particularly in the countries with the lowest levels of income given their lower resilience and higher socioeconomic vulnerability.

Changement climatique dans les pays en développement : effets du réchauffement climatique, mécanismes de transmission et politiques d'adaptation

RÉSUMÉ

Sur la base d'un panel de 126 pays à revenu faible ou intermédiaire sur 1960-2017, nous trouvons que des écarts de température positifs et durables par rapport à leur norme historique ont un effet négatif non linéaire sur la croissance économique et par habitant. Dans le pays médian, une augmentation soutenue de la température de 1°C réduit la croissance annuelle du PIB réel par habitant de 0,74 à 1,52 point de pourcentage. Nous constatons aussi que la montée des températures affecte l'arbitrage intertemporel des ménages entre consommation et investissement, la part de la consommation privée dans la valeur ajoutée totale augmentant au détriment de l'investissement. Une décomposition sectorielle montre que la part de la valeur ajoutée industrielle diminue également. Alors que la part de la valeur ajoutée agricole augmente, la production et la productivité agricoles diminuent. Dans l'ensemble, nos résultats suggèrent que le réchauffement climatique constitue un piège à pauvreté, compliquant l'adaptation au changement climatique dans les pays en développement, particulièrement dans les pays aux niveaux de revenus les plus faibles en raison de leur faible résilience et de leur forte vulnérabilité socioéconomique.

Mots-clés : changement climatique, croissance économique, adaptation, pays en développement

1 Introduction

Climate change, *i.e.* the changing patterns of temperatures and precipitations, is one of the global challenges of our time. Its growing and global environmental and socio-economic impacts weigh significantly on the current international agenda and on national policymaking. Its impact may however vary significantly according to the level of economic development, with low- and middle-income countries bearing a disproportionate cost, even though they have contributed only marginally to temperature rises, and, in some cases, help mitigate it. This may imply different priorities between mitigation and adaptation policies, in particular using policy toolkits that favor rapid economic growth. This is to ensure economic convergence with developed countries and help reaching Sustainable Development Goals. These policy dilemmas and the risk of collective action failures arising from differences in development levels were recognized by the 2015 Paris Climate Agreement, which includes annual transfer commitments from high-income to developing countries amounting to 100 billion US dollars.

In this article, we examine the macroeconomic consequences of climate change in developing countries. The recent and rapidly growing literature that links temperatures and precipitations to output growth already points to a negative effect on economic growth in the vast majority of both developed and developing countries (Dell et al., 2012, 2014), with possible accelerating and cumulative non-linear effects (Burke et al., 2015b). Using the local projections method with a quadratic specification, Acevedo et al. (2020) also find that temperature hikes reduce output growth. Kahn et al. (2019) use an autoregressive distributed lag approach, without quadratic term, but assess the macroeconomic effect of temperature deviations from their historical norms, instead of temperature levels. Because of the distinct characteristics of low- and middle-income countries (higher demographic growth, lower levels of development and resilience, lower institutional quality), the impact of climate on economic growth (or development, proxied by GDP per capita) may however differ markedly from that in high-income countries both in terms of scope and transmission mechanisms.

To address these issues, we chose to focus on assessing the effect of global warming, defined as sustained positive temperature deviations from their historical norms, on real GDP and real GDP per capita growth, combining economic and climate data to obtain a panel of 126 low- and middle-income countries over the period 1960–2017. We control for sustained precipitations deviations from their historical norms to assess whether climate change effects on output mostly stem from global warming or precipitations.

To complement our analysis, we shed light on the transmission channels by decomposing the GDP into its demand and sectoral components. Finally, we test the impact of policy variables of particular interest for developing countries to assess how they could be effective in attenuating the macroeconomic effect of global warming on output.

This article contributes to the existing literature by introducing significant methodological innovations. First, we depart from earlier studies whose central estimates are obtained from samples that include countries from all income levels. These may underestimate the impact on developing countries, deeply exposed to climate change risks. To address the crucial financial policy and international aid issues to achieve the Sustainable Development Goals, we focus exclusively on low- and middle-income countries.

Second, we abandon the hypothesis that labour productivity is the main transmission channel and consider the possibility of transmission through land productivity. Therefore, we construct the country-year climate observations adopting an agnostic approach and we compute them as the unweighted average of gridded climate observations within land boundaries.

Third, we depart from the use of weather shocks and adopt a variant of the local projections method introduced in Ramey and Zubairy (2018) to capture the effects of sustained temperature and precipitations deviations from their historical norms on per capita output growth over different horizons. In addition to being closer to the policy question of interest, *i.e.* assessing the effects of climate change instead of weather shocks, this strategy may reduce the bias introduced by the use of the contemporary shock while controlling for the forward values of the independent variable within the horizon (Ramey and Zubairy, 2018).

Fourth, we complement this analysis by inspecting the underlying transmission mechanisms, both on the demand and the supply sides, before discussing the role of policy variables. Our results provide additional insights on how climate change affects economic growth in developing countries

In a first exercise, we find that global warming has a substantial and sustained negative impact on GDP (and GDP per capita) growth in developing countries. In the median country, a sustained 1°C increase in temperature lowers real GDP per capita annual growth rate in 1.13 percentage points (0.74–1.52 p.p., 90% confidence interval), while the effect of precipitation deviations is not economically significant, in line with recent studies. We then confirm the robustness of this result by presenting a series of tests that consist in excluding China, Russia and India, three countries which have had a non-negligible contribution to climate change and which could introduce an issue of reverse causality, using real GDP instead of real GDP per capita as a dependent variable, controlling for the occurrence of natural disasters, the levels of temperatures and precipitations and the effects of terms of trade movements, using Driscoll and Kraay standard errors, and adding country-specific linear and quadratic time trends to control for gradual changes to countries' growth rates that may be due to country-specific time-varying factors.

In the second exercise on transmission mechanisms using both demand and sectoral components, we find that global warming increases the relative share of private consumption and decreases that of investment, possibly reflecting more binding subsistence requirements in a context of a declining output and income. We also find that global warming leads to an increase of the share of the agricultural value-added in GDP at the expense of industrial value-added, despite a decline in agricultural output growth, leading to a potential reinforcement of the "food problem". Both the sectoral and the demand decomposition of GDP indicate a shift towards short-term gains at the cost of investment, economic diversification and future prosperity.

In a third exercise, we discuss the role of several potential adaptation policies, such as electrification, deforestation, coal consumption, exchange rate regime or institutional quality, to attenuate the negative effect of global warming on output growth in developing countries. We do not consider the effects of such policies on climate change itself through increased greenhouse gases emissions, *i.e.* whether they are compatible or not with mitigation efforts. Some of these policies could therefore be considered as maladaptation policies. Causal inference from this exercise is more difficult, but the results seem to indicate that a higher level of development is associated with a smaller effect of global warming on per capita output growth.

In sum, since our results also indicate that development becomes more difficult to achieve as temperatures rise, we find that global warming reinforces development traps, threatens the gains in living standards, particularly since the beginning of the 21st Century, and will hinder further adaptation to climate change in developing countries. Even though is it not explicitly related to climate change, the Covid-19 crisis illustrates the importance of some of such regressive effects brought about by natural disasters.

The remainder of the article is organized as follows. Section 2 reviews the literature and Section 3 describes the data and introduces some stylized facts on climate change. Section 4 details the empirical strategy. Section 5 presents the results of the global warming effects on output as well as robustness checks, Section 6 analyses the transmission mechanisms and Section 7 discusses the effects of adaptation policies. Finally, Section 8 concludes.

2 Review of the Literature

An early topic of interest (Ibn Khaldun, 1377; Montesquieu, 1748), the climate-economic growth nexus has become a research topic of paramount importance with increasing global concerns about climate change. Some literature strings highlight the role played by geography and climate conditions for economic development (Diamond, 1997; Sachs, 2003), while others, such as Acemoglu et al. (2002) and Rodrik et al. (2004), argue that institutions are the ultimate determinant of development, at least within the historical human climate niche (Xu et al., 2020). Easterly and Levine (2003) point out that the impact of geography, climate, greatly depends on human institutions and how they adapt geography and human activity and institutional design and adaptation, for example in facilitating or preventing the spread of infectious diseases. Such authors, as well as observation, indicate that there is no simple and deterministic relation between climate and economic growth and a rapidly growing string of theoretical and empirical research has uncovered a large scale of micro and macro transmission channels between climate and economic activity. This ample literature on the relation between economic activity and the main variables of climate change, temperatures and precipitations, is reviewed in Dell et al. (2014), Carleton and Hsiang (2016), Heal (2017) and Auffhammer (2018), among others.

The main theoretical approach to analyze this nexus, pioneered by Nordhaus (1977), is to build comprehensive, partial or general equilibrium, quantitative models (Integrated Assessment Models - IAMs). These models include the DICE model (Nordhaus, 1992, 2008), as well as a great number of other specifications introduced in Rezai et al. (2012), Kompas et al. (2018), Barnett et al. (2020) and Alestra et al. (2020). In these models, economic activity interacts with the climate through greenhouse gas (GHG) emissions from production and a climate damage function. Such approaches are well-suited to capture cross-country or cross-region heterogeneity (Bretschger and Valente, 2011) but are highly sensitive to underlying assumptions on the discount factor (Dietz et al., 2020, as already stressed in the earlier Nordhaus/Stern debate), the exclusion of the financial sector (Lamperti et al., 2019) or risk incorporation (Cai et al., 2013). They are more likely to underestimate damages than empirical alternative approaches (Lancesseur et al., 2020), leading to potentially significant underestimations of the optimal carbon price. This has led authors to question their relevance (Pindyck, 2013) or find agents-based alternatives with stochastic individual weather shocks (Lamperti et al., 2018). The specification and calibration of the damage function, which captures the economy's response to rising temperatures, are critical (Weitzman, 2010) and entail high uncertainty (Tol, 2002).

Recent empirical literature has therefore sought to provide more robust calibrations of the damage function. Such studies aim at estimating economic damages arising from high frequency or annual weather shocks over a large palette of transmission channels. The relevance of such transmission channels may vary from region to region and according to economic development.

The agricultural sector is both highly sensitive and vulnerable to climate change. In developed countries, Deschênes and Greenstone (2007) project a modest positive effect of increased temperatures and precipitations on agricultural output in the US. Using Californian data and an instrumental variable approach, Hagerty (2020) finds a decline in crop production when water is scarce and that inefficient adaptation strategies have not enabled to raise revenues. Burke and Emerick (2016) also find little effects of adaptation in the U.S. agricultural sector, with strong negative impacts of temperature hikes on crop yields.

The impact of climate change on the agricultural sector is crucial in developing countries, where this sector represents a larger share of output and employment and the key to subsistence for the most vulnerable populations exposed to both poverty, malnutrition and the direct effects of climate change. Taraz (2018) finds evidence of farmers adaptation in India, but with limited success in the face of extreme heat rises. Aragón et al. (2018) find that farmers in Peru adapt to climate change through increased land use to cope with lower production from increased temperatures, but at the cost of future productivity. Auffhammer and Kahn (2018) review more extensively the challenges that farmers in developing countries may need to tackle in order to adapt to climate change, which include higher income volatility, bad harvests, animal malnutrition and crop choice, among others.

Climate change may also affect human capital and hence labour productivity. Using U.S. data, Barreca et al. (2015) find that abnormally high temperatures are associated with lower fertility rates 9 months later, while Barreca and Schaller (2019) find that hot weather increases the risk of shorter gestation. Kim et al. (2019) also evidence a negative relation between extreme temperatures and maternal and infant health, and Ranson (2014) finds a positive relation between temperatures and criminal acts. Sun et al. (2019) show that climate change will induce an increase in health heat stress that will primarily affect developing countries.

Another strand of the literature focuses on the relation between weather shocks and conflicts. In a historical perspective, Christian and Elbourne (2018) find that lower precipitations increased the likelihood of Roman emperors assassination because of military agitation at the frontiers due to starvation, and Fenske and Kala (2015) argue that the African slave trade increased in cold years due to cost reductions stemming from lower mortality and higher yields. For more recent periods, Burke et al. (2009)

find strong linkages between civil war and temperature in Africa, with warmer years leading to significant increases in the likelihood of war. McGuirk and Nunn (2020) and Eberle et al. (2020) find a relation between precipitation and temperature shocks, respectively, and conflict between herders and farmers. The mechanisms imply competition for scarce resources, and the results suggest that appropriate institutions help mitigate these negative effects of weather shocks. The literature review by Hsiang and Burke (2014) and the meta-analysis by Hsiang et al. (2013) conclude that the magnitude of climate's influence on modern conflict is both substantial and highly statistically significant, with a vast set of possible transmission mechanisms.

Because of this diversity, the enumerative approach, by summing up sectoral effects, has not been successful in providing better calibrations of the damage functions (Lancesseur et al., 2020). Hence, a recent strand of the literature has focused on various aggregate macroeconomic variables, such as real GDP and real GDP per capita, to disentangle the net economic effects of weather shocks.

Macroeconometric VAR models have evidenced that business cycles in both high-income and developing small island countries are vulnerable to weather shocks and natural disasters (Buckle et al., 2007; Cashin and Sosa, 2013). Building an estimated DSGE model, Gallic and Vermandel (2020) show that climate matters for New Zealand's business cycle through land productivity, shift in farmers' demand for goods and real exchange rate movements.

Using sub-national data for the U.S. economy, Colacito et al. (2019) find that temperature hikes reduce GDP growth, and Hsiang et al. (2017), by looking at the probable effects of climate change on a wide set of economic outcomes, also conclude that climate change will negatively affect the GDP and will increase spatial inequalities. Using a precipitation-evapotranspiration index, Couharde and Généroso (2017) show that hydro-climatic conditions affect economic growth in predominantly agricultural developing countries. Couharde et al. (2019) evidence, using the same index, that the effects of El Niño and La Niña episodes on real GDP per capita in low- and middle-income countries depend on local weather conditions and are greater in tropical, humid countries.

In a highly influential paper using cross-country panel data, Dell et al. (2012) find that higher temperatures not only substantially reduce economic growth, but also have wide-ranging effects affecting the agricultural and industrial sectors, as well as political stability. Burke et al. (2015b) point out that these effects on economic activity may be cumulative and nonlinear, necessitating the use of quadratic specifications. The authors find that the effect of higher temperatures on productivity is negative in both developing and high-income countries but dwindles as economies get wealthier, and that impacts increase as temperature rises. They conclude that global income inequality is likely to increase because poorer countries are warmer, a result confirmed in Diffenbaugh and Burke (2019).

Using the local projections method with a quadratic specification, Acevedo et al. (2017) and Acevedo et al. (2020) find that in warmer low- and middle-income countries (but not in temperate high-income countries), higher temperatures negatively affect output growth because of reduced agricultural output, suppressed productivity of workers exposed to heat, slower investment and poorer health. Abandoning the quadratic specification, Acevedo et al. (2019) conclude that adaptation policies have had a limited capacity to attenuate the negative effects of higher temperatures on output growth.

After developing a theoretical framework in which labour productivity is the main transmission mechanism, Kahn et al. (2019) use an ARDL approach with a linear specification and consider temperature and precipitation deviations from their historical norms instead of their levels. Contrary to much of the literature (Tol, 2018), the authors find that positive temperature deviations negatively affect real per capita output growth in both developing and high-income countries. Precipitation deviations have no statistically significant effects, confirming the results found in numerous studies. The fact that most recent papers find negative effects of temperature shocks on output growth, and not only on the level of output, increases concerns on the projected economic impacts of climate change due to the compounding effect. Burke et al. (2018), among others, discuss the economic benefits from limiting temperatures rise.

Economic activity may also be affected by natural disasters, a large proportion of which may be sensitive to climate change. Recent research has focused on short-run economic effects of (climate-related) natural disasters (Klomp and Valckx, 2014; Kousky, 2014; Lazzaroni and van Bergeijk, 2014). Skidmore and Toya (2002) find positive effects of disasters on growth, with reduced losses from disasters when the economy develops (Toya and Skidmore, 2007). Building a fictious counterfactual using the synthetic control method, Cavallo et al. (2013) find no effects of large natural disasters on growth once political turmoil is controlled for. Closing important methodological caveats of earlier studies, Strobl (2012) finds that natural disasters weigh on growth in the short-term, especially in developing countries (Noy, 2009). To take into account the endogeneity between natural disasters and socio-economic conditions (Kahn, 2005), Felbermayr and Gröschl (2014) advocate using physical measures of disasters and also find that they have negative effects on growth.

The seemingly contradictory findings may stem from the diversity of disaster types (Fomby et al., 2013; Loayza et al., 2012) and heterogeneous transmission mechanisms (Mohan et al., 2018). Such effects include the capital stock (Acevedo, 2016), trade flows (El Hadri et al., 2018, 2019), public finances (Lis and Nickel, 2010; Acevedo, 2014; Klomp, 2017), the financial sector (Albuquerque and Rajhi, 2019; Brei et al., 2019; Keerthiratne and Tol, 2017; Klomp, 2014), fiscal and monetary policy (Ouattara and Strobl, 2013; Klomp, 2020), household income and welfare (Carter et al., 2007; Arouri et al., 2015; Keerthiratne and Tol, 2018), aggregate welfare (Cantelmo et al., 2019) or religiosity (Sinding Bentzen, 2019).

Evidence on the effects of natural disasters on economic activity in the long run is however still inconclusive (Noy and duPont IV, 2016). While climate models' predictions about future temperatures and precipitations are uncertain (Burke et al., 2015a), these models are not able yet to predict precisely enough the future changes in the frequency and intensity of extreme natural events Hsiang and Kopp (2018). As shown in Weitzman (2009), our inability to value the cost of cataclysmic events that occur with an unknown tiny probability might lead us to underestimate the costs of climate change.

As discussed notably in Hsiang (2016), recent research on the economic impact of climate change points to important distinctions to make between natural disasters, weather shocks and climate change. Climate change can be defined as the joint probability distribution describing the state of the multi-dimensional atmosphere, ocean, and freshwater systems (Hsiang and Kopp, 2018) whereas better identified weather shocks are specific draws from this probability distribution (Tol, 2020). To reconcile these two notions, we build upon the literature that assesses the effects of weather shocks and construct a measure of temperature and precipitation deviations from their historical norms that retains the advantageous econometric properties of these variables. We then consider a variant of the local projections method introduced in Ramey and Zubairy (2018) which allows to capture the response of output to a cumulative shock in temperature and precipitation deviations from their historical norms over different horizons that include from 1 to 6 years. Specifying such sustained temperature and climate deviations, *i.e.* climate change, instead of using weather shocks is in our view a better fit to answer the policy question of interest. It also eliminates biases associated with the inclusion of forward values of the independent variables as controls (Ramey and Zubairy, 2018).

Controlling for natural disasters may contribute to clarify the effects of such large-scale climate-driven events that may cloud the relationship between global warming and economic activity, at least in the short run. Finally, focusing on developing countries will help us tailor our model specifications to their specific characteristics, reduce the risk of under-estimation and assess how these may affect the path to sustainable growth in a more tractable way.

3 Data and Stylized Facts

To assess the effect of global warming on economic activity in low- and middle-income countries (as defined by the 2019 World Bank classification, shown in appendix Figure A.1), we construct a country-level dataset covering 126 countries over the period 1960 - 2017. Sample selection is exclusively based on data availability, and the detailed list of countries is indicated in appendix Table A.1. The dataset covers three dimensions: socio-economic variables, climate-related disaster and climate variables, and carbon emissions and consumption. Appendix Table A.2 lists all the data sources used in this paper.

3.1 Socio-Economic data

The main dependent variables, real GDP per capita and real GDP, are obtained from the International Financial Statistics (IFS) and World Development Indicators (WDI) dataset. The WDI dataset is also the main source for alternative dependent variables: private, public and total consumption, investment and fixed investment, imports, exports and trade balance, as well as the shares of real value added of services, manufacturing and industry. Agricultural data (Total Factor Productivity - TFP, output, inputs, labour, machinery, fertilizers and livestock) are obtained from the United States Department of Agriculture (USDA - ERS, 2019). The Human Development Index is retrieved from the UNDP - HDI (2019), commodity exports value is obtained from Gruss and Kebhaj (2019) and TFP from the Penn World Tables version 9.1 (Feenstra et al., 2015).

The total growth of a variable over a period is computed as the log difference of this variable between the end and the beginning of period.

3.2 Climate data

Monthly land temperature and precipitation data are from the University of Delaware (Matsuura and Willmott, 2019). The global dataset is gridded with a 0.5°latitude × 0.5°longitude resolution (approximately 55km near the equator) and covers the period 1900–2017. Country-level data are obtained by computing the unweighted average of all the observations within the land boundaries of each countries.

Contrary to the methodology used mostly for developed countries (Dell et al., 2012; Burke et al., 2015b; Acevedo, 2016; Kahn et al., 2019, among others), we do not weight the climate observations by local population density. In addition to endogeneity issues, particularly in long periods (due to climate-induced migration), such a strategy is not optimal in the case of developing countries where economic activity may not coincide with the distribution of population.

First, climate conditions can affect output through capital destruction during extreme events with distant impacts. For instance, El Niño costero strongly impacted the coastal regions of Southern Ecuador and Northern Peru in 2017, but most of it adverse effects, from floods and landslides, or *huaicos*, resulted from heavy rainfalls in the western slope of the Andes mountain range, in addition to the coastal areas.[1] Exceptional floods in western France in May and June 2016 were also due to heavy rainfalls upstream, while global value chains reinforce the economic relevance of remote climatic conditions.[2]

Second, the economic production might not be located where population density is high, particularly in countries that rely heavily on natural resources (e.g oil production in the Sahara desert and population close to the Mediterranean in Algeria, or the strong impact of the melting of the scarcely populated Artic sea ice). Weighting climate data by the population density might impede to capture climate variations that matter for production and economic outcomes.

Third, agricultural production, a major component of GDP in many LICs and MICs, may be determined by upstream as much as local climate conditions, especially when it relies on irrigation. The Egyptian economy, prior to the erection of the Aswan dam, provides a famous example: rainfalls in Ethiopia used to determine the fate of Egyptian farmers and Egypt's economy, while local climatic conditions were of relatively little importance. Peru provides another, less extreme example, as its coastal and Andean agriculture (located in relatively highly populated areas) depends on high altitude precipitations originating from the Amazon basin. In this context, weighting local climate variables by population density provides no benefits in terms of identification. More importantly, both irrigated and rainfed agriculture usually occur where population density is relatively low, raising further concerns on the robustness of weighting climate observations by population density.

3.3 Carbon Dioxide Emissions

Historical data on CO_2 country emissions from the beginning of industrialization (1751 in the UK) are retrieved from Boden et al. (2017). Time series were combined (e.g. Yemen) or split (e.g. Czechoslovakia before 1992) to take into account changes or merging of states over time. Historical data from split series are based on the relative

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[1] As evidenced in https://www.dhn.mil.pe/Archivos/Oceanografia/ENFEN/nota_tecnica/01-2017.pdf.

[2] Floods in Thailand caused major hikes in hard drive prices globally in 2011.

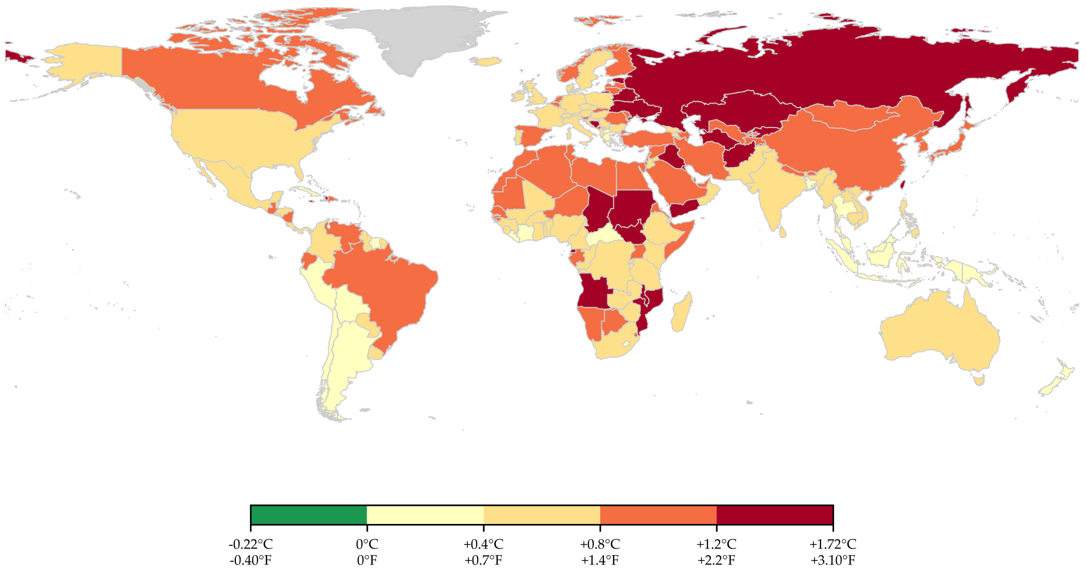
weight in the first year of their separation. The historical observations corresponding to colonies are not included.

Country territorial CO_2 emissions and transfers, corresponding to the difference between CO_2 consumption and territorial emissions, are retrieved from Friedlingstein et al. (2019) and allow to expand the time coverage of CO_2 emissions until 2017.

3.4 Climate Change: A Descriptive Analysis

There is a scientific consensus on the fact that the climate has changed since the pre-industrial period (1850–1900 according to the definition from the Intergovernmental Panel on Climate Change – IPCC). Because the data does not cover this period, we chose 1900–1950 as a reference for our sample.

Figure 1 – Yearly Temperature difference: 2001-2017 Vs. 1900-1950



Source: Matsuura and Willmott (2019), elaborated by the authors. Units are in Celsius and Fahrenheit degrees.

Figure 1 shows the average mean temperature deviation between the early 21st and 20th centuries, *i.e.* between 2001–2017 and 1900–1950. Except for 6 small countries and administrative regions (with declines ranging from -0.1 to -0.22°C), all countries mean temperature have increased over time.[3] The mean temperature deviation is higher than 1°C (*i.e.* 1.8°F) in 42 countries and higher than 1.2°C (*i.e.* 2.2°F) in 24 countries, mainly from Sub-Saharan Africa, the Middle East and Central Asia, and Eastern Europe and Russia. On average, country mean temperatures are 0.75°C (1.35°F) higher in 2001–2017 than in 1900–1950.

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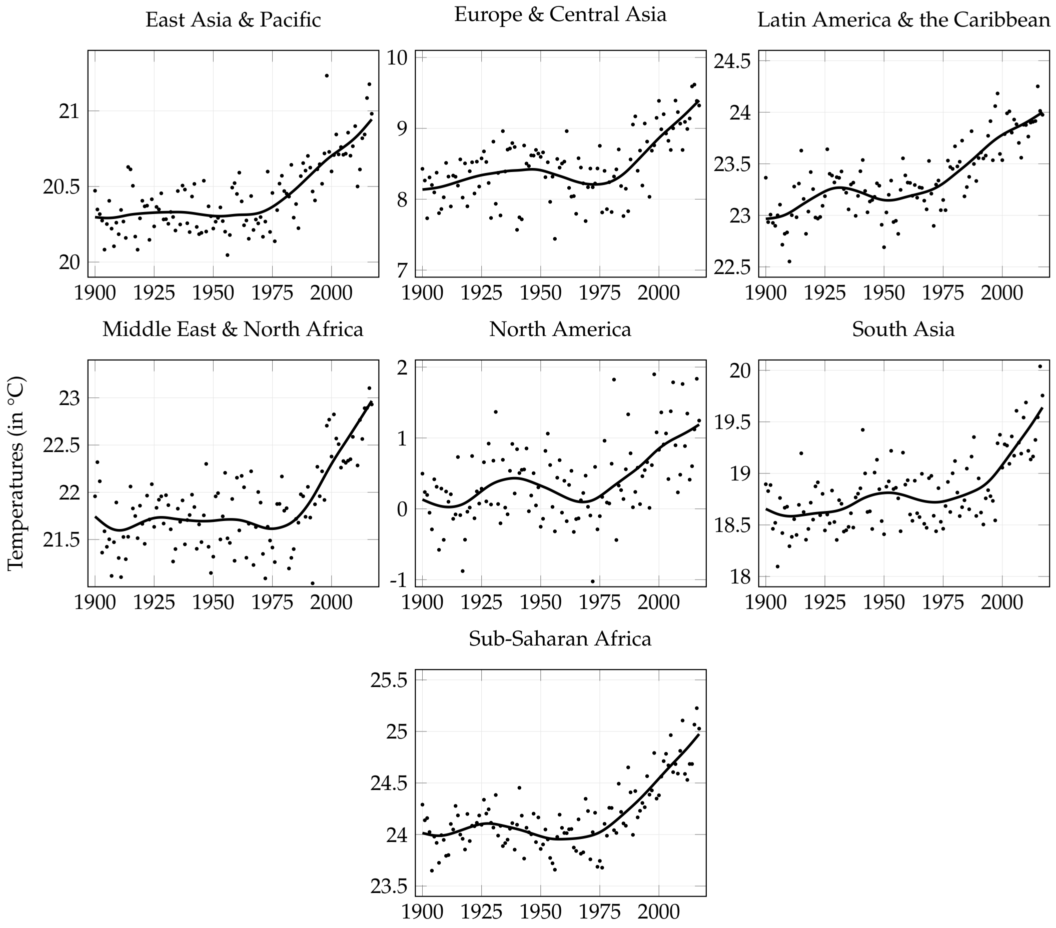
[3] Mean temperatures have lightly declined only in Singapore (-0.22°C), Macao, Hong Kong, Comoros, Samoa and Malta

Figure 2 – Temperature Dynamics (1900 - 2017), by Region



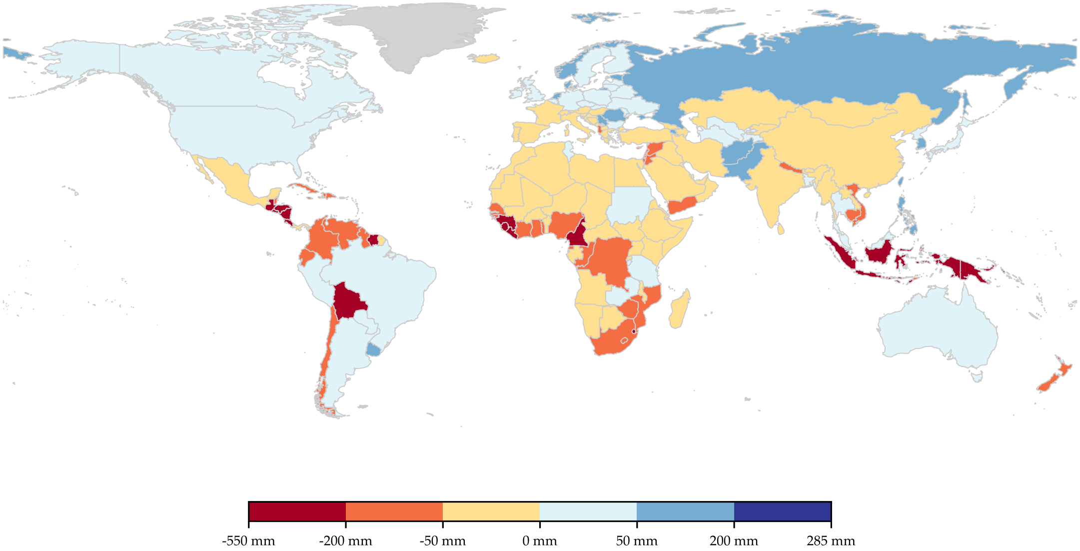
Source: Matsuura and Willmott (2019), calculations of regional temperatures by the authors using the unweighted average of country yearly mean temperatures and smoothing by the Hodrick–Prescott filter ($\lambda = 1600$).

This global increase is associated with substantial country variations, including between neighbouring countries: Mexico and Guatemala (temperature increase 1.8 times higher in Guatemala), Cuba and Haiti (6.7 times higher in Haiti), Jordan and Iraq (1.6 times higher in Iraq), the Central African Republic and Chad, Sudan and South Sudan (4.1 to 4.5 times higher).

Figure 2 shows the dynamic evolution of temperatures across economic regions (World Bank classification) between 1900 and 2017. Although temperature levels differ substantially between regions (and between countries within regions), a structural break can be observed in all regions between 1970 and 1980 (earlier in Latin America and the Caribbean): broadly constant until then, temperatures exhibit a positive trend until today, while the volatility of yearly mean temperature seems to decline over time (to be confirmed by further analysis).

As shown in Figure 3, yearly total precipitations deviation between 2001–2017

Figure 3 – Yearly Precipitations difference: 2001-2017 Vs. 1900-1950



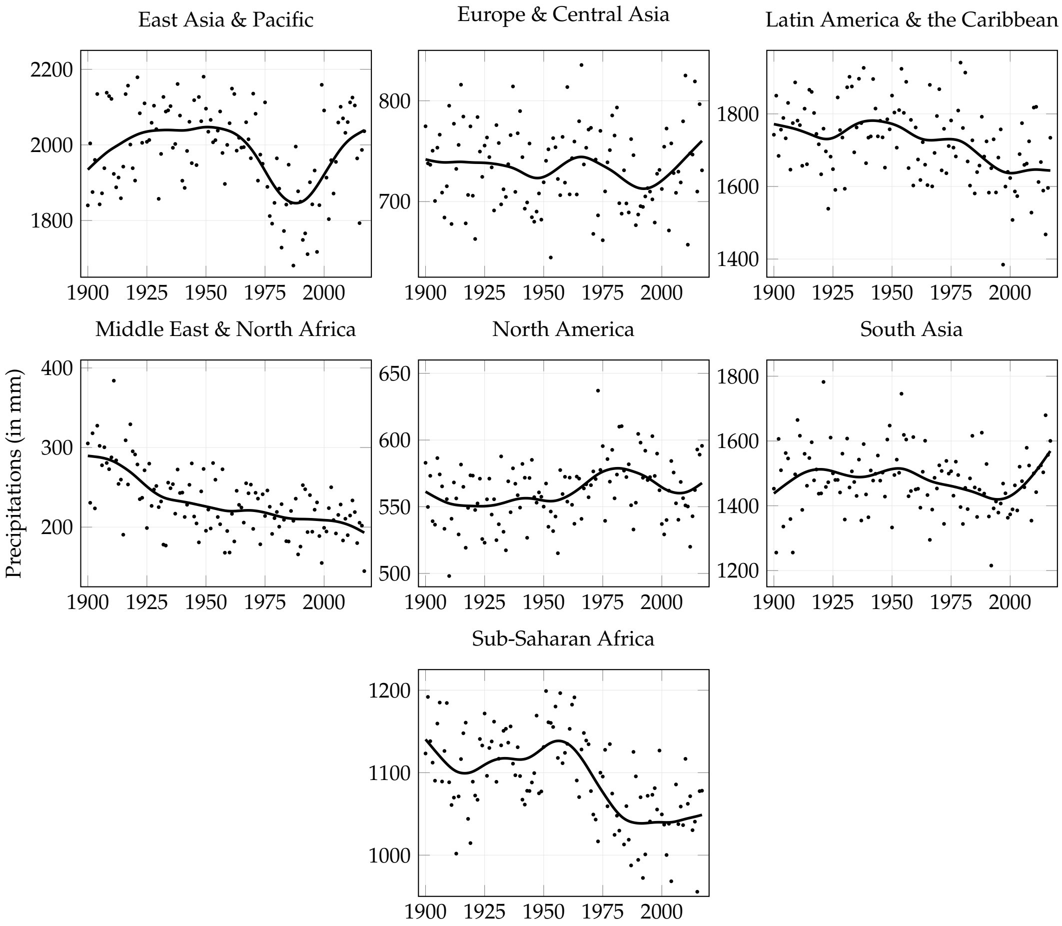
Source: Matsuura and Willmott (2019), elaborated by the authors. Units are in Millimeters.

and 1900–1950 are more scattered. While precipitations have increased in 57 countries (45 mm on average), they are below historical levels in 128 countries (-83 mm on average). Country yearly precipitations have declined in 44 mm on average between the beginning of the 21st and the 20th centuries. In 14 countries, mainly located in Central America, Western Africa and Southeast Asia, this decline in absolute terms has been more dramatic and greater than 200 mm.

As evidenced in Figure 3 and Figure 4, the heterogeneity of precipitations patterns between countries and regions is greater than in the case of temperatures, and no global pattern can be detected by visual inspection. While global and country-level temperature dynamics is unequivocal, yearly and country-level precipitations observations might not be the optimal scale to detect macroeconomic effects, due to the importance of the locality and temporality of rainfalls, in line with the literature on the macroeconomic impact of climate change.

Finally, CO_2 data shows a strong divide between developing and developed countries, with strong implications for the econometric assessment of the impact of climate change on economic activity. First, there is little doubt that climate change can be attributed to human activity, and more specifically to greenhouse gas (GHG) emissions (see Bindoff et al., 2013; Cook et al., 2016; Hsiang and Kopp, 2018, among others). Figure 5 panel a shows that the global level of carbon dioxide (CO_2) emissions each year is at a historical peak, while Figure 5 panel b shows that the growth rate of global CO_2 emissions does not slow down. These patterns are problematic, notably because emissions at year t have an impact that will materialize for a long period (see Hsiang and

Figure 4 – Precipitations Dynamics (1900 - 2017), by Region



Source: Matsuura and Willmott (2019), calculations of regional precipitations by the authors using the unweighted average of country yearly total precipitations and smoothing by the Hodrick–Prescott filter ($\lambda = 1600$).

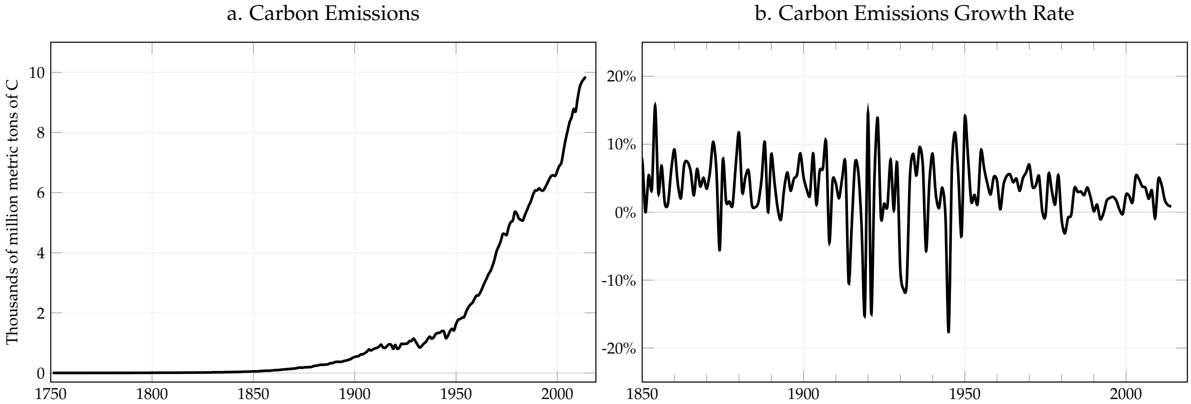
Kopp, 2018, for a detailed description of the physics involved).

Second, as shown in Figure 6, while temperature increases and precipitation declines have generally affected middle- and low-income countries to a greater extent than high-income countries, the latter have been the primary contributor to global CO_2 emissions. The vast majority of low- and middle-income countries have only had a marginal contribution, below 1% or even 0.5% of historical global CO_2 emissions.

Third, while weather shocks seem to be relatively exogenous, econometric assessments of the effects of sustained climate deviations from historical norms may be biased due to reverse causality issues: economic growth, which lead to CO_2 emissions, does positively affect temperatures.

For these reasons, assessing the effects of climate change on economic activity in low- and middle-income countries based on coefficients estimated on a global sample that includes high-income countries may lead to an underestimation of the effects of

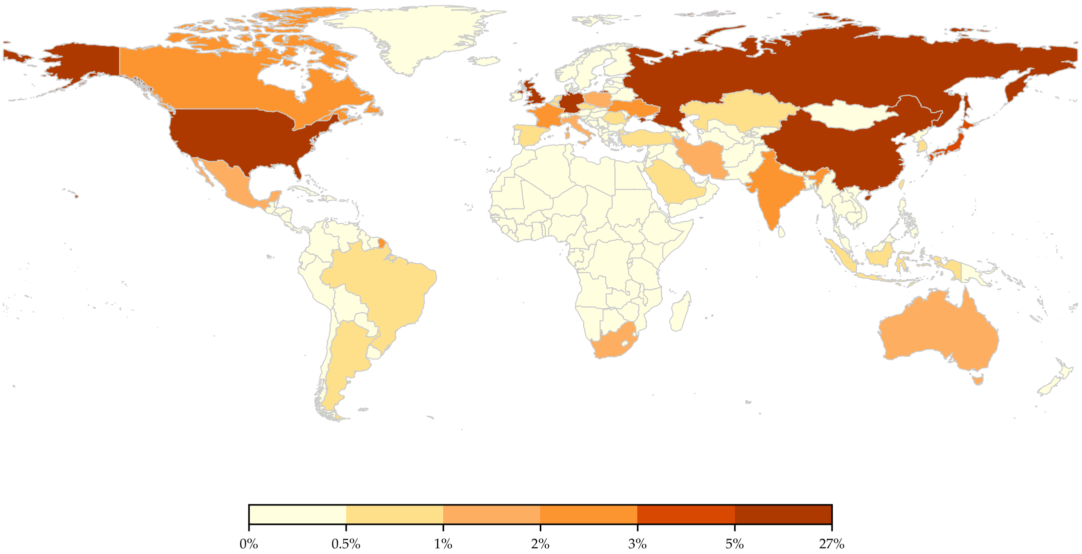
Figure 5 – Global Carbon Dioxide Emissions, 1751 - 2014



Sources: Boden et al. (2017), elaboration by the authors. Emissions correspond to total carbon dioxide emissions from fossil fuel consumption and cement production.

climate change. Because low- and middle-income countries have not had yet a significant impact on CO_2 emissions and therefore climate change, restricting the sample to these countries ensures the exogeneity of the dependent variables. Because three middle-income countries, China, India and Russia, have had a significant contribution to historical CO_2 emissions, these countries will be excluded from the sample in a robustness check.

Figure 6 – Share of Total Historical Carbon Dioxide Emissions, in 2014



Source: Boden et al. (2017), elaborated by the authors. Emissions correspond to total carbon dioxide emissions from fossil fuel consumption and cement production.

4 Empirical Framework

We adopt the local projections method introduced in Jordà (2005) to assess the cumulative response of output to temperature deviations from their historical norms and separately estimate equation (1) for horizons $h = 0, 1, ..., 5$:

$$\begin{aligned} y_{i,t+h} - y_{i,t-1} = \theta_h \sum_{p=t}^{t+h} \widetilde{T_{i,p}} + \phi_h \sum_{p=t}^{t+h} \widetilde{P_{i,p}} + \vartheta_h \sum_{p=t}^{t+h} \widetilde{T_{i,p}}^2 + \varphi_h \sum_{p=t}^{t+h} \widetilde{P_{i,p}}^2 + \lambda \mathbf{X'}_{i,t} \\ + \alpha_i^h + \gamma_t^h + \varepsilon_{i,t}^h \end{aligned} \tag{1}$$

where i denotes the country and t the year. y_t denotes the log of real GDP per capita, and therefore the dependent variable $y_{i,t+h} - y_{i,t-1}$ captures the total growth of real GDP per capita in years t to $t+h$. $\widetilde{T_{i,t}}$ denotes the deviation in mean temperature of country i in year t from its historical values and $\widetilde{P_{i,t}}$ the deviation in total precipitations in year t from its historical values. In the benchmark specification, $\mathbf{X'}_{i,t}$ is a vector of control variables that include two lags of the dependent variables, $\Delta y_{t-1} = y_{t-1} - y_{t-2}$ and Δy_{t-2}, as well as two lags of the main independent variables, $\widetilde{T_{i,t-1}}$, $\widetilde{T_{i,t-2}}$, $\widetilde{P_{i,t-1}}$, $\widetilde{P_{i,t-2}}$, $\widetilde{T_{i,t-1}}^2$, $\widetilde{T_{i,t-2}}^2$, $\widetilde{P_{i,t-1}}^2$, $\widetilde{P_{i,t-2}}^2$.

This set of control variables remains parsimonious on purpose so that the estimates are not affected by the issue of over-controlling, as discussed in Dell et al. (2014). In robustness checks and alternative regressions, additional control variables are included to the vector $\mathbf{X'}_{i,t}$. α_i^h denotes country fixed effects and captures country-specific time-invariant factors, such as geography and history, that may affect real per capita GDP growth, and γ_t^h denotes time fixed effects that capture common shocks, such as the international business cycle.

Contrary to a large strand of the literature that assess the effect of temperature level on economic growth (Acevedo et al., 2020, 2019; Dell et al., 2012; Burke et al., 2015b, among others), we follow Kahn et al. (2019) and assess the effect of temperature deviations from their historical norms. This variable allows to suppress the cross-country differences in temperature levels and follows more closely the concept of climate change, while country fixed effects capture the average temperature level of each country over the period. We construct the temperature deviations from their historical norms, $\widetilde{T_{i,t}} = T_{i,t} - \overline{T_{i,1900-1950}}$, as the deviation in mean temperature of country i in year t ($T_{i,t}$) with respect to the average yearly mean temperature of country i over the period 1900–1950, in Celsius degrees (°C), and the precipitations deviation from their historical norms, $\widetilde{P_{i,t}}$, as the deviation in total precipitations in year t with respect to the average yearly total precipitations of country i over the period 1900–1950, in millimeters (mm). Because pre-industrial temperatures and precipitations are not available in the dataset we use, we consider the period 1900–1950 as the historical norm.

We define the effect of temperature deviations from their historical norms on output as the cumulative real GDP per capita variation relative to the cumulative temperature deviations from their historical norms during a given period. This definition makes it possible make advances in providing insight on the impact of climate change, *i.e.* sustained deviations of temperatures from historical averages beyond short-run effects, while keeping the advantages of using random climate shocks in terms of identification (Tol, 2018).

Most papers assessing the macroeconomic effects of climate change have used large panel data sets comprising as many countries as allowed by data availability, including when assessing the macroeconomic effects of climate change in developing countries. However, as discussed in Kahn et al. (2019), reverse causality issues are likely to arise: if climatic conditions might affect GDP, the scientific consensus argues that the reverse is true, as large quantities of CO_2 and other greenhouse gases are emitted by economic activity. As the global climate depends on recent and historical greenhouse gases emissions (Hsiang and Kopp, 2018), and because a high share of historical CO_2 emissions has been produced by high income countries (figure 6), our identification strategy deals with the reverse causality issue by including only low- and middle-income countries in our sample, *i.e.* those which have historically made a marginal contribution to global greenhouse gases emissions. We address potential concerns about China, Russia and India, all responsible for a significant share of historical CO_2 emissions, by excluding them from the sample as robustness checks.

5 Macroeconomic Effects of Global Warming

5.1 Main Results

Table 1 presents the main estimates from equation (1) for each horizon, using real GDP per capita growth (Panel A) and real GDP per capita growth (Panel B) as dependent variables. The results show a non-linear relation between temperature deviations from their historical norms and real GDP per capita and real GDP growth since the estimate for the linear term is positive and statistically significant from horizon $h = 2$ and the quadratic term is negative and statistically significant from horizon $h = 1$. As is usually found in the empirical literature that assesses the macroeconomic effects of weather shocks and climate change, the estimates for precipitations deviations from their historical norms are not statistically significant. They become statistically significant from horizon $h = 3$, but remain economically not significant.

Table 1 – Macroeconomic Effects of Temperature Deviations from their Historical Norms in Low- and Middle-Income Countries

	$h=0$	$h=1$	$h=2$	$h=3$	$h=4$	$h=5$
Panel A: Dependent variable is Real GDP per capita growth						
$\widetilde{T}$	-0.002	0.005	0.008***	0.010***	0.010***	0.011***
	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)
$\widetilde{T}^2$	-0.002	-0.005***	-0.008***	-0.009***	-0.009***	-0.010***
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
$\widetilde{P}$	-0.000	-0.000	-0.000*	-0.000**	-0.000**	-0.000**
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
$\widetilde{P}^2$	-0.000	-0.000	0.000	0.000	0.000	0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Obs.	5814	5684	5554	5424	5294	5164
R^2	0.08	0.12	0.15	0.15	0.15	0.16
Panel B: Dependent variable is Real GDP growth						
$\widetilde{T}$	-0.003	0.003	0.007**	0.008***	0.009***	0.010***
	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)
$\widetilde{T}^2$	-0.002	-0.005***	-0.007***	-0.008***	-0.008***	-0.008***
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
$\widetilde{P}$	-0.000	-0.000	-0.000*	-0.000**	-0.000**	-0.000*
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
$\widetilde{P}^2$	-0.000	-0.000	0.000	0.000	0.000	0.000**
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Obs.	5820	5690	5560	5430	5300	5170
R^2	0.08	0.11	0.13	0.14	0.14	0.14

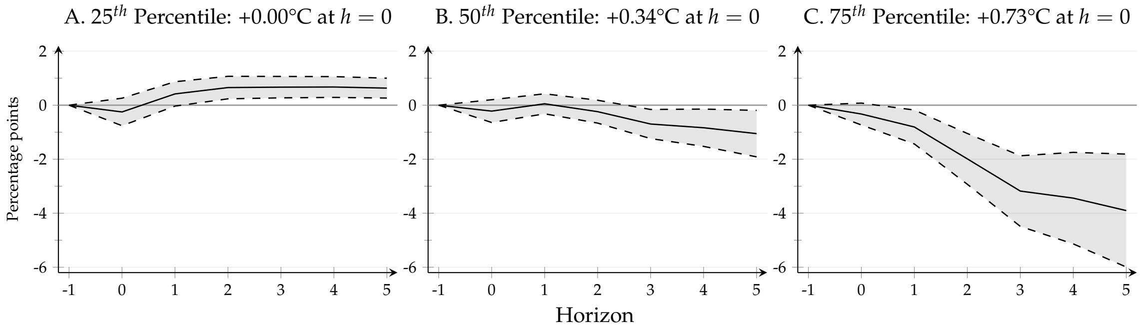
Note: Control variables are included in the regressions but not reported. Standard errors are in parentheses. * Significant at the 10 percent level, ** Significant at the 5 percent level, *** Significant at the 1 percent level.

Equation (2) indicates the total, non-linear effect of temperatures deviations from their historical norms on real GDP per capita growth for a given year t and horizon $h \in [0,5]$:

$$\frac{\partial\left(y_{i,t+h}-y_{i,t-1}\right)}{\partial\widetilde{T_{i,t,h}}}=\theta_h+2\vartheta_h\widetilde{T_{i,t,h}} \tag{2}$$

Equation (2) is obtained by partially differentiating equation (1) with respect to temperatures deviation from their historical norms and allows to compute the cumulative impulse response function of real GDP per capita to temperature deviations. In order to be representative of both the time and the country dimensions of the sample, the presentation of the results takes into consideration two different measures of

Figure 7 – Cumulative Effect of Temperatures Deviations from their Historical Norms on per Capita Real GDP, Using Temperatures of the Full Sample



Note: The three panels show the cumulative response of per capita real GDP to a 1 °C increase in temperatures deviation from their historical norms. The distribution of these temperatures deviations is computed over the entire sample, since year 1960, and the values are as follows: +0.004°C, +0.34°C and +0.73°C for the 25^{th}, 50^{th} and 75^{th} percentiles, respectively, at $h = 0$, and +0.27°C, +1.83°C and +3.93°C °C for the 25^{th}, 50^{th} and 75^{th} percentiles, respectively, at $h = 5$. See Table 2 panel A for complete details on the values at each horizon.

temperature deviations from their historical norms.

Figure 7 reports the cumulative impulse response of real GDP per capita growth to temperature deviations from their historical norms using, for each horizon, the 25^{th} percentile, the median and the 75^{th} percentile of the distribution of these temperatures deviations for the entire sample, *i.e.* since year 1960. Table 2 panel A reports, for each horizon, the distribution of these temperature deviations for the full sample.

Temperature deviations from their historical norms for the 25^{th} percentile have been modest over the period, amounting to 0.004°C for horizon $h = 0$ and 0.3°C for horizon $h = 5$. Figure 7 panel A evidences that such small deviations did not negatively affect real GDP per capita, and even had a slightly positive effect of 0.63 percentage points of real GDP per capita total growth over a 6 years horizon ($h = 5$), or equivalently of 0.10 percentage points of annual growth rate[4]. At the median and the 75^{th} percentile of the distribution, temperature deviations are significantly higher and reach, respectively, +0.34°C and + 0.73°C at horizon $h = 0$, and +1.83°C and +3.93°C at horizon $h = 5$. The results presented in Figure 7 panels B and C show that these positive temperature deviations have a negative effect on real GDP per capita growth. At the median (Figure 7 panel B), temperature hikes lead to a 1.05 percentage points decline in real GDP per capita total growth over a 6 years horizon (or a 0.16 percentage points decline in real GDP per capita annual growth rate), and to a 3.9 percentage points decline in total growth over a 6 years horizon (or a 0.60 percentage points decline in annual growth rate) at the 75^{th} percentile.

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[4] This calculation of the change in the annualized growth rate, and the following ones, assume a 2 percent real GDP per capita annual growth rate in a scenario without of climate change.

While this presentation of the results allow to understand the macroeconomic effect of global warming in developing countries during the period 1960–2017, it is not fully representative of each country's individual experience, since a country need not be in the same category of the distribution each year and at each horizon. Furthermore, the materialization of climate change, global warming, was not perceived yet at the beginning of the period.

Table 2 – Distribution of Temperatures Deviations from Their Historical Norms

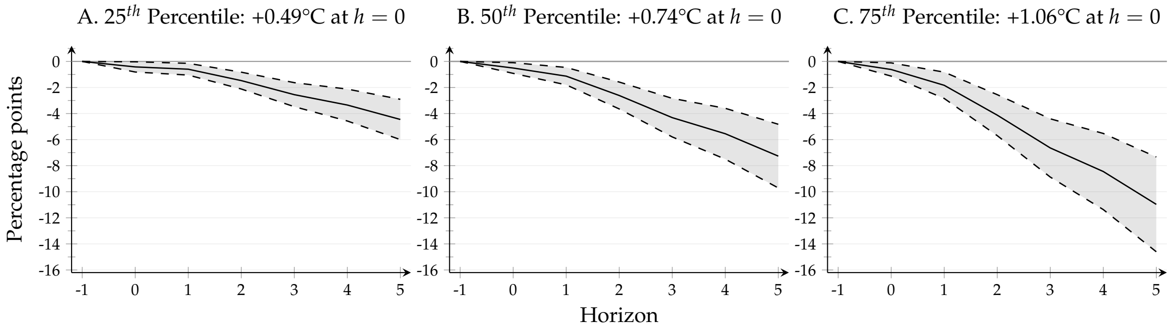
Panel:	*A. Full Sample of Estimations*			*B. Early 21st Century*		
Percentile:	25th	50th	75th	25th	50th	75th
$\widetilde{T_{h=0}}$	+0.004	+0.335	+0.729	+0.491	+0.737	+1.061
$\widetilde{T_{h=1}}$	+0.044	+0.658	+1.409	+0.981	+1.474	+2.123
$\widetilde{T_{h=2}}$	+0.100	+0.967	+2.046	+1.472	+2.211	+3.184
$\widetilde{T_{h=3}}$	+0.166	+1.248	+2.671	+1.963	+2.948	+4.245
$\widetilde{T_{h=4}}$	+0.204	+1.540	+3.309	+2.453	+3.685	+5.306
$\widetilde{T_{h=5}}$	+0.272	+1.830	+3.931	+2.944	+4.422	+6.368

Note: All temperature changes are in °C. To convert into °F, multiply by nine-fifth. $\widetilde{T_h}$ denotes the deviation in mean temperature from its historical values during horizon h. Panel A indicates for horizons $h = 0, ..., 5$ the 25th, 50th and 75th percentiles of the distribution of yearly mean temperature deviations from the average of yearly mean temperatures during period 1900 - 1950 in the full sample, used to obtain the results presented in Figure 7. Panel B indicates for horizons $h = 0, ..., 5$ the 25th, 50th and 75th percentiles of the difference between the averages of yearly mean temperatures of the periods 2001–2017 and 1900–1950.

Figure 8 also reports the cumulative impulse response of per capita output to temperature deviations from their historical norms and the coefficients θ_h and ϑ_h are still estimated by equation (1) using the full sample, but the temperature deviations from their historical values correspond to the 25th percentile, the median and the 75th percentile of the country average mean temperature deviations between the periods 2001–2017 and 1900–1950 presented in Figure 1. For horizons $h > 0$, the mean temperature deviation is multiplied by $h + 1$. The distribution of this variable is reported in Table 2 Panel B. For simplicity, and because it is more reperesentative of each country's recent and ongoing exeprience, the remainder of the paper uses this distribution of temperature deviations.

The results presented in Figure 8 show the recent macroeconomic effects of global warming in developing countries and evidence that these negative effects are large and have increased in the most recent period. The results are statistically significant from horizon $h = 0$ for the country at the 25th percentile, the median and the 75th percentile of the distribution. The country at the 25th percentile of the distribution,

Figure 8 – Cumulative Effect of Temperatures Deviations from their Historical Norms on per Capita Real GDP, Using Recent Temperatures



A. 25th Percentile: +0.49°C at $h = 0$

B. 50th Percentile: +0.74°C at $h = 0$

C. 75th Percentile: +1.06°C at $h = 0$

Note: The three panels show the cumulative response of per capita real GDP to a 1 °C increase in temperatures deviation from their historical norms. The distribution of these temperatures deviations refers to the difference in average mean temperature between the periods 2001–2017 and 1900–1950, shown in Figure 1. The values are as follows: +0.49°C, +0.74°C and +1.06°C for the 25th, the 50th and the 75th percentiles, respectively, at $h = 0$, and are multiplied by $h + 1$ for each horizon $h > 0$. See Table 2 panel B for complete details on the values at each horizon.

which has experienced an average temperature deviation of 0.49°C in 2001–2017 from its historical norms, looses on average 4.45 percentage points of real GDP per capita total growth over a 6 years horizon ($h = 5$), which corresponds to a 0.68 percentage points decline in real GDP per capita annual growth rate. These loss of real GDP per capita total growth amount to 7.26 percentage points for the median country over a 6 years horizon (*i.e.* a 1.13 percentage points loss in annual growth rate) and 10.97 percentage points for the country at the 75th percentile of the distribution (*i.e.* a 1.73 percentage points loss in annual growth rate).

Table 3 column (1) reports the estimated coefficients used in Figure 7 and Figure 8. At horizon $h = 5$, the effect of temperature deviations from their historical norms on real GDP per capita is non-linear: positive for small temperature deviations but negative for cumulative deviations greater than a total of 0.55°C over six years.

Contrary to much of the related literature, precipitations deviations from their historical norms appear to also have a statistically significant non-linear effect, since the coefficients of both the linear and quadratic terms are negative and significant. However, the results indicate that these deviations do not have economically significant effects: a one-litre cumulative deviation in annual precipitations over the six years horizon leads only to a 0.0012 percentage point decline in real GDP per capita growth.

The fact that none of the coefficients are statistically significant at horizon $h = 0$ while all are at horizon $h = 5$ evidences that sustained changes in weather conditions, *i.e.* a variable that captures more closely the materialization of climate change, impact economic output beyond the short-term effects of weather shocks.

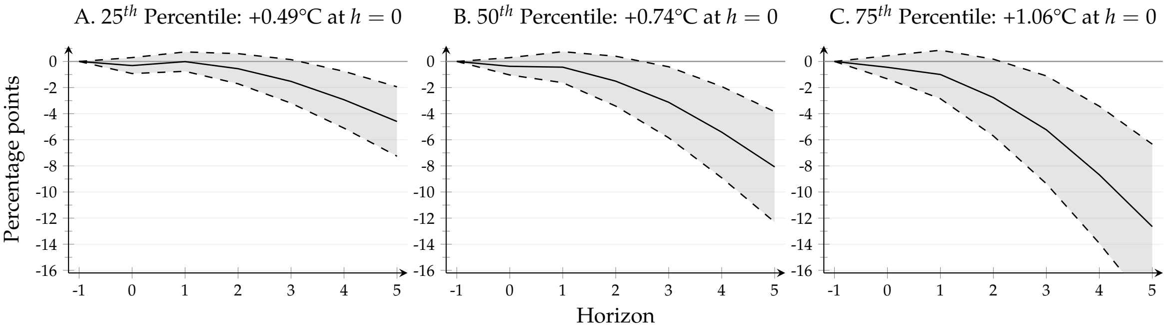
To assess whether temperature deviations from their historical norms have differentiated effects in countries with the lowest level of income per capita, we add interaction terms to equation (1) where the indicator function $\mathbb{1}_{\text{(low inc.)}}$ takes the value of 1 if country i at year t has an income level below the 33rd percentile of the sample for that year. This definition is broadly consistent with the low-income category of the World Bank and this approach is more flexible than using World Bank or IMF lists of countries. After this modification, equation (1) is transformed as indicated in equation (3):

$$\begin{aligned} y_{i,t+h} - y_{i,t-1} = {} & \theta_h \sum_{p=t}^{t+h} \widetilde{T_{i,p}} + \vartheta_h \sum_{p=t}^{t+h} \widetilde{T_{i,p}}^2 + \zeta_h \sum_{p=t}^{t+h} \widetilde{T_{i,p}} \times \mathbb{1}_{\text{(low inc.)}} + \kappa_h \sum_{p=t}^{t+h} \widetilde{T_{i,p}}^2 \times \mathbb{1}_{\text{(low inc.)}} \\ & + \phi_h \sum_{p=t}^{t+h} \widetilde{P_{i,p}} + \varphi_h \sum_{p=t}^{t+h} \widetilde{P_{i,p}}^2 + \iota_h \sum_{p=t}^{t+h} \widetilde{P_{i,p}} \times \mathbb{1}_{\text{(low inc.)}} + \eta_h \sum_{p=t}^{t+h} \widetilde{P_{i,p}}^2 \times \mathbb{1}_{\text{(low inc.)}} \\ & + \lambda \mathbf{X'}_{i,t} + \alpha_i^h + \gamma_t^h + \varepsilon_{i,t}^h \end{aligned} \tag{3}$$

Equation (4) indicates the total, non-linear effect of temperatures deviations from their historical norms on real GDP per capita growth in countries with the lowest level of income per capita for a given year t and horizon $h \in [0, 5]$:

$$\frac{\partial \left(y_{i,t+h} - y_{i,t-1}\right)}{\partial \widetilde{T_{i,t,h}}} = \left(\theta_h + \zeta_h\right) + 2\left(\vartheta_h + \kappa_h\right) \widetilde{T_{i,t,h}} \tag{4}$$

Figure 9 – Cumulative Effect of Temperatures Deviations from their Historical Norms on per Capita Real GDP in Lowest Income Countries, Using Recent Temperatures



Note: The three panels show the cumulative response of per capita real GDP to a 1 °C increase in temperatures deviation from their historical norms in countries with an income per capita level below the 33th percentile of the sample. The distribution of the temperatures deviations refers to the difference in average mean temperature between the periods 2001–2017 and 1900–1950, shown in Figure 1. The values are as follows: +0.49°C, +0.74°C and +1.06°C for the 25^{th}, the 50^{th} and the 75^{th} percentiles, respectively, at $h = 0$, and are multiplied by $h + 1$ for each horizon $h > 0$. See Table 2 panel B for complete details on the values at each horizon.

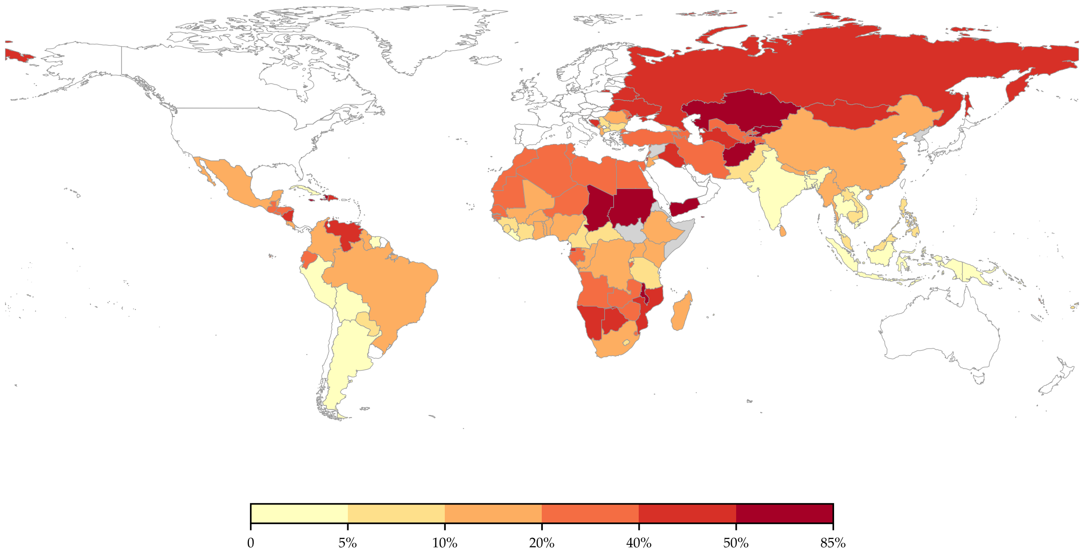
Figure 9 reports the effects of recent global warming in countries with the lowest level of income per capita. Uncertainty increases slightly around the estimates, but these remain statistically significant for horizons $h = 3, 4$ and 5 and close to the estimate of the full sample.

5.2 Cumulative Effects of Climate Change on Income per Capita

We use the estimates for horizon $h = 5$ reported in Table 1 to assess the annualized losses in real GDP per capita growth due to temperature deviations from their historical norms and build a counterfactual growth rate corresponding to a scenario without global warming. We then compound the counterfactual annual growth rates over the period 1960–2017.

Figure 10 reports the difference, expressed in percent, between the counterfactual level of real GDP per capita, absent of global warming, and the observed level.

Figure 10 – Real GDP per Capita Loss due to Global Warming (1960–2017)

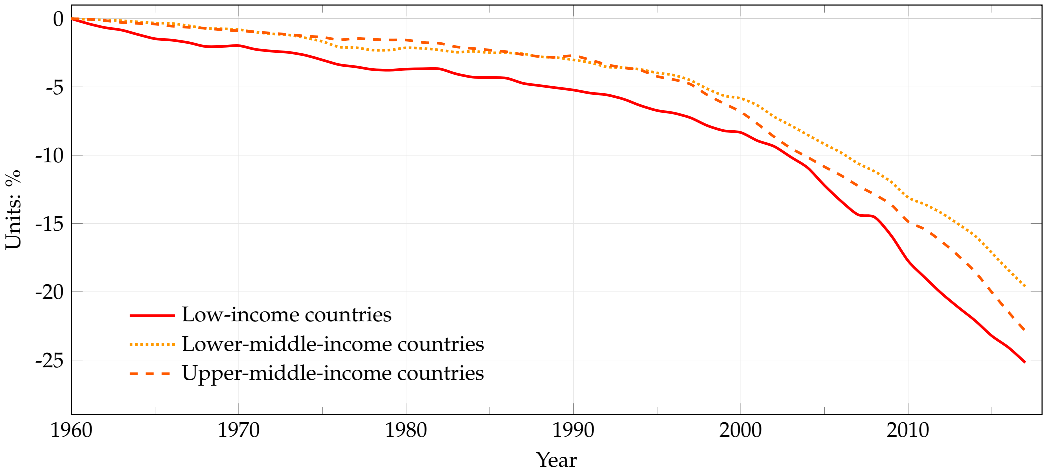


Source: elaborated by the authors. Countries in gray have missing data, countries in white are not included in the sample. The Figure indicates the cumulative loss in real GDP per capita in 2017 with respect to a counterfactual scenario characterized by mean annual temperatures equal to the historical norm (1900–1950) in each year throughout the period (1960–2017).

Real GDP per capita losses with respect to the counterfactual scenario amount to 22% on average, but these losses are unevenly distributied, reflecting differences in temperature hikes across countries. The mose affected regions appear to be Central Asia, Austral, Saharan and Sahelian Africa as well as the Caribbean. Ten countries (dark red in Figure 10) have experienced losses amounting to 50% or more of the real GDP per capita of the counterfactual scenario.

Figure 11 shows the dynamics of real GDP per capita losses since 1960 in developing countries, according to their relative income levels.

Figure 11 – Real GDP per Capita Loss due to Global Warming, by Income Category



Source: elaboration by the authors. The figure indicates for each income category the unweighted average of countries' cumulative loss in real GDP per capita with respect to a counterfactual scenario characterized by mean annual temperatures equal to the historical norm (1900–1950). Income categories correspond to the 2019 World Bank classification.

In all income groups, real GDP per capita losses have accelerated around year 2000 and amounted to 20 to 25% of their levels in the counterfactual scenario, *i.e.* absent of climate change. The economic impacts of global warming are however slightly higher in low-income countries, reflecting higher temperature rises on average. This suggests additional challenges for this group of countries given their lower resilience and higher socioeconomic vulnerability: a given macroeconomic impact has larger consequences on their ability to ensure sustainable development (see the policy Section 7).

5.3 Robustness

Table 3 columns (2) to (8) summarize a series of robustness checks for horizons $h = 0$ and $h = 5$. The upper parts of Panel A and Panel B indicate the estimates using equation (1) and the bottom part of each panel indicates the effects at the 25^{th}, the 50^{th} and the 75^{th} percentiles of the distribution of country average mean temperature deviations between the periods 2001–2017 and 1900–1950, using equation (2). The respective cumulative impulse response functions that detail the results for all horizons and use the same distribution for temperature deviations are presented in Appendix B.

Table 3 column (2) reports the results excluding China, India and Russia from the sample and evidences that, despite their relatively high contribution to historical global

Table 3 – Macroeconomic Effects of Temperature Deviations from their Historical Norms in Low- and Middle-Income Countries: Main Results and Robustness Checks

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
				Panel A: Contemporary effects ($h = 0$)				
$\widetilde{T}$	-0.250	-0.267	-0.250	-0.697**	-0.250	-0.061	-0.312	0.141
	(0.311)	(0.315)	(0.320)	(0.326)	(0.311)	(0.181)	(0.312)	(0.296)
$\widetilde{T}^2$	-0.174	-0.193	-0.174	0.003	-0.174	-0.096	-0.169	-0.371*
	(0.187)	(0.191)	(0.237)	(0.193)	(0.187)	(0.118)	(0.187)	(0.190)
$\widetilde{P}$	-0.000	-0.000	-0.000	0.000	-0.000	-0.000	-0.000	0.000
	(0.000)	(0.000)	(0.001)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
$\widetilde{P}^2$	-0.000	-0.000	-0.000	-0.000	-0.000	-0.000	-0.000	-0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Obs.	5814	5681	5814	5381	5814	8298	5820	5814
R^2	0.08	0.08		0.07	0.08	0.09	0.08	0.13
At 25th	-0.421*	-0.456*	-0.421**	-0.694***	-0.421*	-0.155	-0.479**	-0.223
percentile	(0.238)	(0.243)	(0.202)	(0.244)	(0.238)	(0.158)	(0.239)	(0.228)
At 50th	-0.506**	-0.551**	-0.506**	-0.692***	-0.506**	-0.203	-0.562**	-0.405*
percentile	(0.250)	(0.256)	(0.224)	(0.252)	(0.250)	(0.176)	(0.250)	(0.245)
At 75th	-0.619**	-0.676**	-0.619*	-0.690**	-0.619**	-0.266	-0.672**	-0.646**
percentile	(0.309)	(0.317)	(0.323)	(0.309)	(0.309)	(0.222)	(0.310)	(0.313)
				Panel B: Cummulative effects ($h = 5$)				
$\widetilde{T}$	1.148***	1.165***	1.148**	0.759***	1.345***	0.254	0.975***	3.120***
	(0.279)	(0.282)	(0.525)	(0.277)	(0.303)	(0.164)	(0.281)	(0.310)
$\widetilde{T}^2$	-0.951***	-0.937***	-0.951**	-0.990***	-0.959***	-0.264**	-0.845***	-2.057***
	(0.188)	(0.190)	(0.371)	(0.182)	(0.187)	(0.111)	(0.189)	(0.238)
$\widetilde{P}$	-0.001**	-0.001**	-0.001	-0.001	-0.001**	-0.001**	-0.001*	-0.000
	(0.000)	(0.000)	(0.001)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
$\widetilde{P}^2$	0.000	0.000	0.000	0.000**	0.000	0.000	0.000**	0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Obs.	5164	5046	5164	4756	5164	7376	5170	5164
R^2	0.16	0.16		0.15	0.16	0.11	0.14	0.40
At 25th	-4.453***	-4.352***	-4.453**	-5.071***	-4.300***	-1.300**	-4.002***	-8.992***
percentile	(0.939)	(0.956)	(2.019)	(0.909)	(0.944)	(0.603)	(0.946)	(1.244)
At 50th	-7.265***	-7.122***	-7.265**	-7.998***	-7.134***	-2.081**	-6.501***	-15.074***
percentile	(1.485)	(1.510)	(3.095)	(1.439)	(1.487)	(0.926)	(1.496)	(1.939)
At 75th	-10.967***	-10.768***	-10.967**	-11.851***	-10.865***	-3.108**	-9.791***	-23.080***
percentile	(2.210)	(2.247)	(4.525)	(2.143)	(2.210)	(1.356)	(2.226)	(2.859)

Dependent variables (first difference of the logarithm of real GDP per capita and real GDP) are multiplied by 100 so that estimated coefficients can be interpreted as percentage points. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

carbon emissions, including these countries to the sample does not lead to biased results since the estimates are close to the baseline estimates, reported in column (1). Column (3) reports the estimates with Driscoll and Kraay standard errors, that are robust to cross-sectional dependence and autocorrelation, additionally to heteroskedasticity (Driscoll and Kraay, 1998). Statistical significance decreases but remains from horizon $h = 2$ at the 25^{th} percentile and from horizon $h = 1$ at the median and the 75^{th} percentile, as shown in appendix Figure B.2.

Céspedes and Velasco (2014) and Fernández et al. (2018) argue that commodity export value have large effects on developing countries' business cycle. Because this variable may be affected by weather shocks, especially when the country is pricemaker in global markets, it may confound the effects of weather shocks on economic output. Table 3 column (4) reports the estimates controlling for commodity export value contemporary growth rate and its two lags. The results show that the effect of temperature deviations from their historical norms on real GDP per capita increases while the standard errors shrink, ensuring therefore the baseline results.

Since the effect of climate variables deviations from their historical norms on economic output might depend on their level, Table 3 column (5) reports the estimates controlling for temperature and precipitations levels. Both the estimates and standard errors do not significantly differ from the baseline results, confirming that the macroeconomic effects of global warming are not entirely driven by climate variables levels but instead by their change over time.

As discussed in section 4, our identification strategy relies on the exclusion of high-income countries from the sample since these countries' economic activity has been responsible for a high share of historical CO_2 emissions. Table 3 column (6) reports the estimates when high-income countries are also included in the sample: the estimates remain negative and statistically significant, but become significantly lower in absolute value than those obtained when the sample is restricted to low- and middle-income countries, as shown in Figure B.5. Therefore, empirically assessing the impact of global warming in low- and middle-income countries based on estimates obtained from samples that include high-income countries is likely to lead to an underestimation of the negative global macroeconomic effects of climate change.

Since real GDP per capita growth rate responds to both economic and populational dynamics and because strong evidence suggests that temperatures and weather shocks do affect population dynamics (Barreca et al., 2015; Barreca and Schaller, 2019; Burke et al., 2009; Ranson, 2014; Xu et al., 2020), Table 3 column (7) reports the estimated effects of temperature deviations from their historical norms on the real GDP growth rate instead of the real GDP per capita growth rate. The magnitude of the effects does not vary substantially and standard errors only slightly increase, suggesting that the macroeconomic effects of temperature deviations are robust to, and surpass, the populational effects during the time-period considered. As evidenced in appendix Figure B.11, these effects are not limited to the economy and reduce the growth rate of the Human Development Index.

Finally, Table 3 column (8) reports the estimates when year fixed-effects in equation (1) are reimplaced with country-specific linear and quadratic time trends to capture within-country changes over the sample period, following the approach introduced in Burke et al. (2015b). Although these trends seem less justified when considering real GDP growth rates than levels, they can control for secular stagnation and convergence dynamics. The estimates for temperature deviations and temperature deviations squared are significant with the expected sign, and the macroeconomic effects remain statistically significant from horizon $h = 1$, as shown in Appendix Figure B.10, despite the fact that a substantial part of the climate variation is captured by the time trends. Appendix Figures B.7 and B.8 reimplace year fixed effects with a common linear and a common linear and quadratic time-trends, respectively, while appendix Figure B.9 includes a country-specific linear time-trend. The results from these four alternative specifications indicate that despite capturing a significant share of climate variations, linear and quadratic time trends do not fully account for the cumulative macroeconomic effects of persistent climate deviations from its historical norms.

Climate change materializes in global warming, *i.e.* temperatures hikes, but also in changes in temperature variability. To capture this penomenon, we included the cumulative deviations in within-year monthly temperature standard-deviation with respect to the historical norm. The coefficients are not statistically significant and the estimates of temperature deviations from their historical norms are not altered.[5]

6 Transmission Channels

This section analyses the macroeconomic channels through which temperature deviations from their historical norms affect real per capita GDP growth. Each regression estimates equation (1) by using a different dependent variable, while keeping two lag values of real per capita GDP growth rate in the vector of control variables $\mathbf{X'}_{i,t}$. For each dependent variable y, the cumulative response functions are obtained from equation (2).

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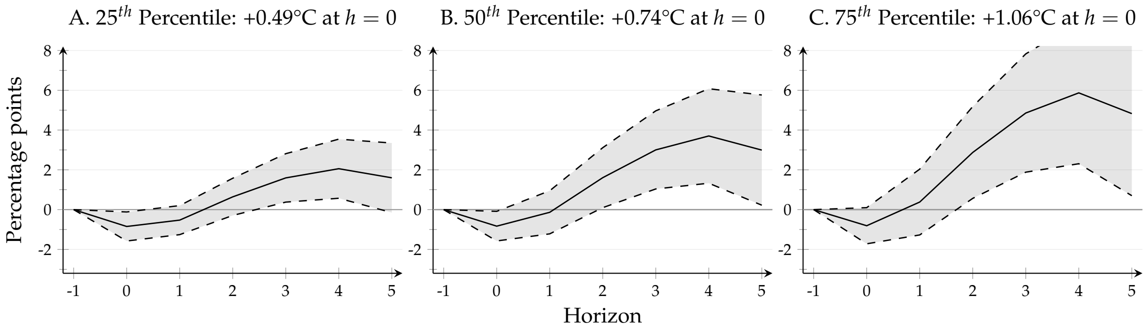
[5] Results available from the authors upon request.

6.1 A Shift in the Composition of Demand

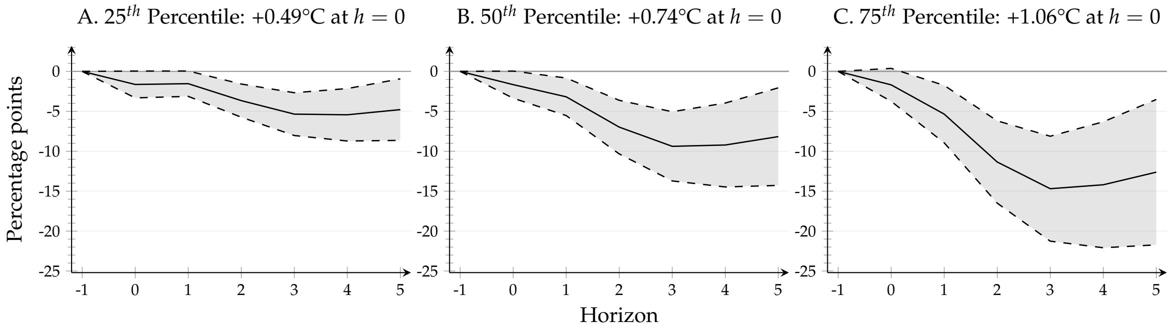
Figure 12 – Cumulative Effect of Temperatures Deviations from their Historical Norms on the Share of Private Consumption in GDP



Note: The three panels show the cumulative response of the ratio of Private Consumption over GDP to a 1 °C increase in temperatures deviation from their historical norms. The distribution of these temperatures deviations refers to the difference in average mean temperature between the periods 2001–2017 and 1900–1950, shown in Figure 1. See Table 2 panel B for complete details on the values at each horizon.

The results presented in Figure 12 show that the share of private consumption in GDP tends to increase when temperatures rise with respect to their historical norms. Furthermore, appendix Figure C.1 shows also a slightly positive effect of temperature hikes on the public consumption share in GDP, resulting in a higher total consumption share in GDP (Appendix Figure C.2). These results suggests that government have attempted to implement adaptive and transition policies through higher public spending, but these policies have not been able to compensate for the negative impact of higher temperatures on output.

Figure 13 – Cumulative Effect of Temperatures Deviations from their Historical Norms on the Share of Investment in GDP

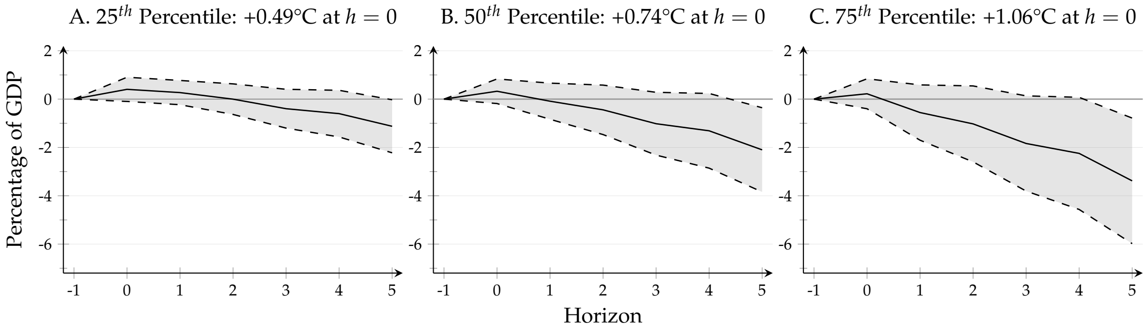


Note: The three panels show the cumulative response of the ratio of Investment over GDP to a 1 °C increase in temperatures deviation from their historical norms. The distribution of these temperatures deviations refers to the difference in average mean temperature between the periods 2001–2017 and 1900–1950, shown in Figure 1. See Table 2 panel B for complete details on the values at each horizon.

Conversely, Figure 13 shows that the share of investment in GDP declines as temperatures rise. Appendix Figure C.3 confirms the negative impact on investment since the share of fixed investments also respond negatively to positive temperature deviations from their historical norms.

Together, these mechanisms raise concerns about long-term economic prospects by suggesting that a sustained increase in temperatures affects the outcome of the intertemporal trade-off between present and future consumption. While no evidence indicates the households' discounting factor might be affected, the results in Figure 8 show that with a declining production, and therefore lower income, the budget constraint also becomes more binding: households in developing countries satisfy their present subsistence requirements, and potentially adapt to a changing climate through higher consumption, at the cost of future prosperity and development. This mechanism suggests that sustained temperatures hikes will likely lead to a reversal of poverty and standard of livings gains from recent years and increases the probability of countries falling into development traps.

Figure 14 – Cumulative Effect of Temperatures Deviations from their Historical Norms on Trade Balance



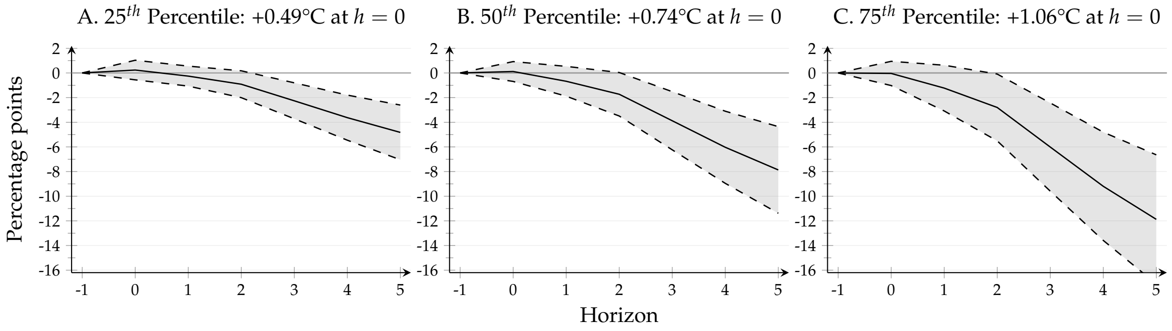
Note: The three panels show the cumulative response of the ratio of Trade Balance over GDP to a 1 °C increase in temperatures deviation from their historical norms. The distribution of these temperatures deviations refers to the difference in average mean temperature between the periods 2001–2017 and 1900–1950, shown in Figure 1. See Table 2 panel B for complete details on the values at each horizon.

The effects of temperature deviations from their historical norms on the trade balance, shown in Figure 14, are more ambiguous and only significant for horizon $h = 5$. For this variable only, which can take a negative value, the dependent variable in equation (1) is modified and corresponds to the total change in the trade balance ratio, expressed in percent of GDP. The overall weakly significant negative response of the trade balance ratio is due to an increased share of imports (Appendix Figure C.6) over long horizons while the effect on exports growth is not statistically significant (Appendix Figure C.7).

6.2 Distinct Sectoral Effects

We also tested sectoral effects to shed light on possible transmission mechanisms of positive temperature gaps with respect to the first half of the 20th century. Figure 15 shows that the growth rate of the share of industry in GDP significantly declines when temperatures deviations are positive. More specifically, the mining, construction, electricity, water, and gas sector are concerned, consistently with the negative response of investment and declining demand for commodity exports. Only the share of manufacture in GDP responds positively (Appendix Figure C.8), possibly reflecting increased outsourcing from industrial to developing countries. This would stem from increasingly stringent environmental and climate-related regulations, in line with the pollution haven hypothesis (see Copeland and Taylor, 1994, for example). The opposite effects on the manufacturing sector on the one hand, and the rest of the industry as well as agriculture on the other hand, can explain the absence of statistically significant effects on export growth: the positive effect of higher manufacturing export on the trade balance appears to be offset by a decline in commodity and cash crops exports.

Figure 15 – Cumulative Effect of Temperatures Deviations from their Historical Norms on the Share of Industrial Value Added in GDP


A. 25th Percentile: +0.49°C at $h = 0$ B. 50th Percentile: +0.74°C at $h = 0$ C. 75th Percentile: +1.06°C at $h = 0$

Note: The three panels show the cumulative response of the ratio of Industrial Value Added over GDP to a 1 °C increase in temperatures deviation from their historical norms. The distribution of these temperatures deviations refers to the difference in average mean temperature between the periods 2001–2017 and 1900–1950, shown in Figure 1. See Table 2 panel B for complete details on the values at each horizon.

While the potential increase in FDI inflows is also expected to positively affect economic outcomes through spillovers on subcontractors in the manufacturing sector and higher demand for high-quality services, appendix Figure C.9 shows that the service sector does not respond positively and remains unaffected by a sustained increase in temperatures.[6]

Sustained temperature hikes have a positive effect on the relative share of the agricultural sector in GDP (Figure 16), i.e. the decline of agricultural output observed

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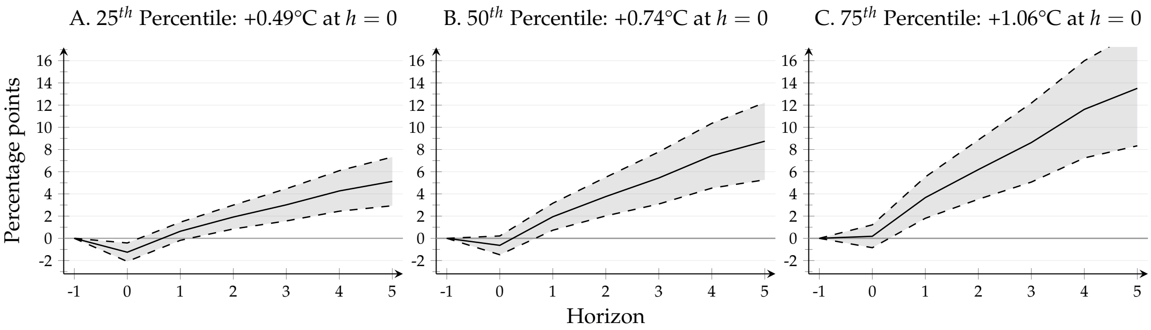
[6] Results presented in Appendix Figure C.5 show no relation between temperatures deviations from their historical norms and TFP growth.

in Figure 17 is less pronounced than that of the industrial sector. This is coherent with the previous results on private consumption due to a tighter budget constraint and the salience of subsistence requirements. This growing importance of the agricultural sector as temperature rises suggests a reinforcement of the "food problem": because of subsistence requirements, developing countries tend to devote a higher share of their resources to food production and consumption (see Gollin et al., 2007; Schultz, 1953).

This challenges the common view that agriculture is that most affected sector by temperature hikes: in spite of large effects of temperature hikes and weather shocks on the agricultural sector shocks (see Ortiz-Bobea et al., 2020, for a recent example), the decline of the agricultural sector is outpaced by that of the secondary sector. This result is in line with the critiques of Integrated Assessment Models (Keen, 2020).

Figure 16 – Cumulative Effect of Temperatures Deviations from their Historical Norms on the Share of Agricultural Value Added in GDP

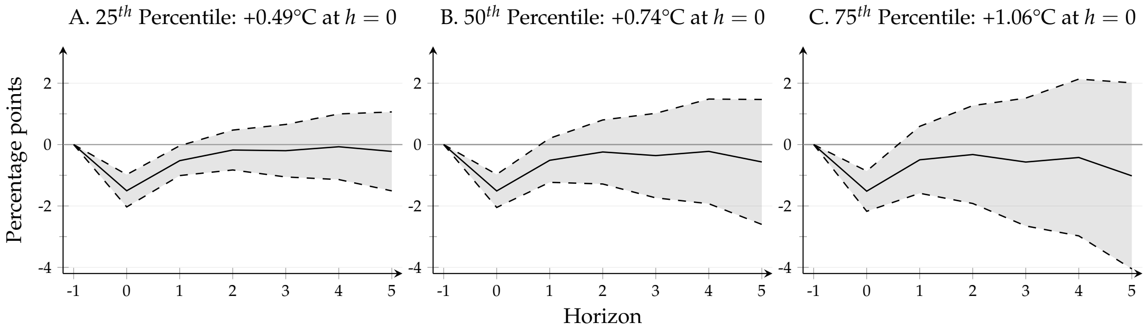


Note: The three panels show the cumulative response of the ratio of Agricultural Value Added over GDP to a 1 °C increase in temperatures deviation from their historical norms. The distribution of these temperatures deviations refers to the difference in average mean temperature between the periods 2001–2017 and 1900–1950, shown in Figure 1. See Table 2 panel B for complete details on the values at each horizon.

Using the International Agricultural Productivity dataset (USDA - ERS, 2019), we assess the effects of temperature deviations from their historical norms on the agricultural sector in more details. Results presented in Appendix C show that temperature hikes translates into a lower use of machinery (Figure C.11) and a decline of agriculture total factor productivity growth (Figure C.10). Sustained temperature hikes also leads to enhanced use of inputs (Figure C.12), fertilizers (Figure C.13) and livestock growth (Figure C.15), a liquid asset often seen as a form of self-insurance. Together, these results suggest a reallocation of available resources in favor of short-term subsistence output at the cost of future productivity. This is coherent with the previously described decline in investment and long-term development prospects.

Global warming threatens recent gains in the fight against poverty and represent a major challenge for the development of low- and middle-income countries. Aggre-

Figure 17 – Cumulative Effect of Temperatures Deviations from their Historical Norms on Agricultural Output



Note: The three panels show the cumulative response of the ratio of Agricultural Output to a 1 °C increase in temperatures deviation from their historical norms. The distribution of these temperatures deviations refers to the difference in average mean temperature between the periods 2001–2017 and 1900–1950, shown in Figure 1. See Table 2 panel B for complete details on the values at each horizon.

gate demand shifts from investment to consumption, increased outsourcing does not appear to be sufficient to maintain the trade balance, the share of industrial output declines while the economy becomes more dependent on agriculture, and agricultural inputs, fertilizers and livestock substitute for investments. While the literature has shown that economic development might be one of the best strategy for developing countries to be able to cope with the economic effects of climate change (Acevedo et al., 2019; Tol, 2018, 2020), our results suggest that it will become increasingly difficult as global temperatures rise.

7 The Role of Structural Policies

This section focuses on the relation between temperature rises and real GDP per capita growth, and how structural policy variables may affect such outcomes. Because of possible reverse causality and correlations with other country characteristics, causal inference is difficult to draw from each individual result presented in this section, but the empirical evidence shown here may provide useful correlations and pointers for possible policy action. Each regression estimates equation (1), with real GDP per capita growth as a dependent variable, in a subsample including only country-year observations that are above (or below) the median value of a specific policy variable for that year. As in the previous sections, the cumulative response functions of the dependent variable y are obtained from equation (2).

Figure 18 panel A show the effect of global warming on real GDP per capita growth when institutional quality is high (above the median, in dark blue) and low (below the median, in light orange). The results indicate that a higher institutional quality

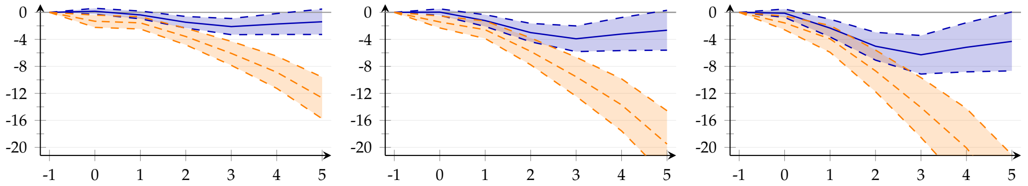
Figure 18 – Cumulative Effect of Temperatures Deviations from their Historical Norms on per Capita Real GDP, According to Policy Levels

Panel A. Institutional Quality

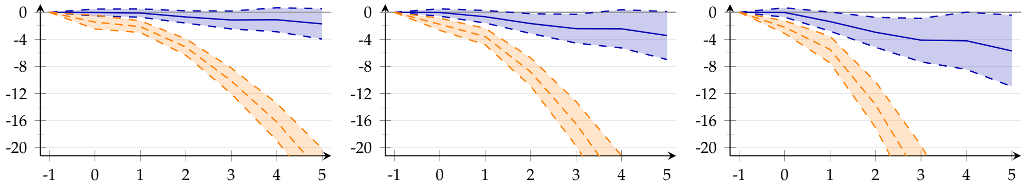
Column i.
25th Percentile: +0.49°C at $h = 0$

Column ii.
50th Percentile: +0.74°C at $h = 0$

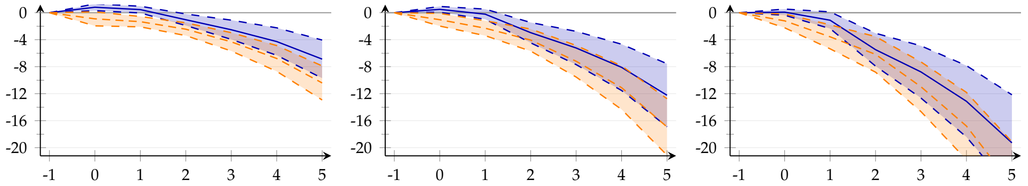
Column iii.
75th Percentile: +1.06°C at $h = 0$



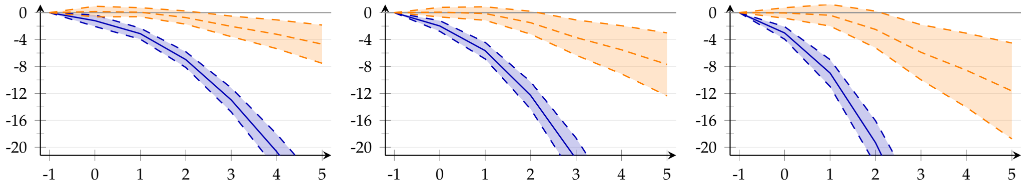
Panel B. Movile Cellular Subscriptions



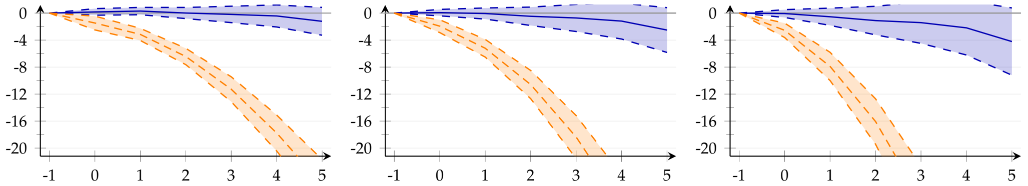
Panel C. Access to Electricity



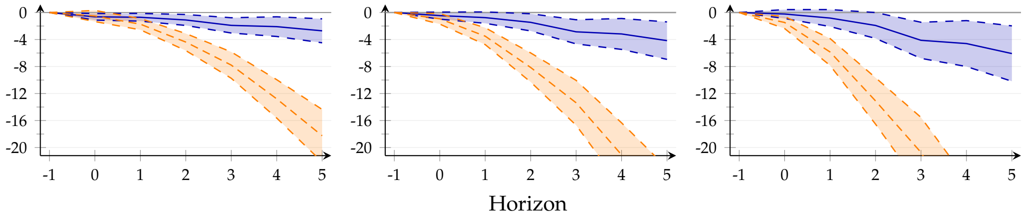
Panel D. Deforestation



Panel E. Coal Consumption



Panel F. De Facto Exchange Rate Regime



Note: Each panel shows the cumulative response of per capita real GDP to a 1 °C increase in temperatures deviation from their historical norms. The dark blue colour includes observations above the respective policy median value, while the light orange colour includes observations below the median.

is associated with a reduced negative impact of temperature hikes on per capita output growth, suggesting that improving institutional quality, in particular in branches of government most affected by climate change, may be instrumental in adapting to and attenuating climate change (Hunjra et al., 2020).

Similarly, Figure 18 panel B shows that the effects of temperature hikes on per capita output growth is all the lower as cell phone subscriptions increase. This may reflect how TICs may contribute to increase economic growth and resilience to changing patterns of climate shocks through better access to information (Janvry et al., 2016; Ceballos et al., 2019) . These technologies may also increase economic resilience with strong leapfrogging effects through increases in firm productivity (Chauvet and Jacolin, 2017) or financial inclusion (Jacolin et al., 2021).

Access to electricity is also associated with a reduced impact, but the evidence is less robust since this effect appears when comparing the country-year observations above the 75^{th} percentile to those below the 25^{th} (Appendix Figure D.1 panel C) but disappears when the threshold is set at the median (Figure 18 panel C).

The impact of deforestation is at first glance ambiguous. Deforestation may be seen as a pro-growth policy since alternative land use (urbanization, agriculture) might often appear to be highly profitable in the short run. However, in addition to their economic value, forests might themselves foster growth in neighbouring regions because of their effectiveness in preventing soil erosion, in protecting agricultural output in the long run, and their major role in the local (and global) climate (Heal, 2020). The results presented in Figure 18 panel D suggest that the latter effect might dominate the former, since a higher rate of deforestation is associated with a more negative effect of temperature deviations on per capita output growth.

Figure 18 panel E shows that a higher level of coal consumption per inhabitant is associated with a reduced effect of temperature hikes on per capita output growth. Coal consumption is positively associated with the size of the manufacturing sector, which favours economic growth in both the short- and the long-run but also contributes to climate change. This suggests that following a free-rider policy might be paying off: developing the manufacturing sector helps reduce the negative economic effects of global warming since this sector appears to be more resistant than others (Appendix Figure C.8) and is growth-enhancing (Rodrik, 2016). However, because they are highly energy-intensive, industrialization policies might also exacerbate climate change, unless investments in energy production favour alternative renewable sources of energy. This externality emerging from industrialization policies underline the necessity for international cooperation to tackle effectively climate change.

The *de facto* exchange rate regime might also matter: the results presented in

Figure 18 panel F show that a more flexible exchange rate regime is associated with a reduced effect of temperature hikes on per capita output growth. This result suggests that exchange rates may be a policy option to adapt to global warming (see also Arcand et al., 2008). This constitutes an interesting topic for further research.

In line with the literature, our results indicate that a wide array of structural policies might serve as adaptation policies and help face the macroeconomic effects of global warming. However, such adaptation policies also become more difficult to implement when temperatures rise as shown in section 6. In our view, these results bring to light a more general pattern: a higher level of development is associated with a lower effect of global warming on per capita output growth and a higher capacity to face the consequences of global warming, while the ability of least developed countries to implement adaptation policies is eroded by temperature rises. For the least developed countries, a horse race has already started between development policies and climate change. Domestic policies should aim at developing the country and building resilience to climate change, but our results suggest that these efforts might not be enough: external financing for climate change adaptation should be substantial and least developed countries should have the priority.

8 Conclusion

This article adds to the recent empirical literature on the macroeconomic effects of climate change by focusing on developing countries and by departing from the hypothesis that labour productivity is the main transmission channel. Instead, our empirical strategy allows to capture the effects through land productivity. The empirical literature has also focused on the effect of weather variables levels or deviations from their historical norm (*i.e.* weather shocks) on per capita output and output growth.

By using the local projections method to capture the effects of sustained temperature and precipitations deviations from their historical norms on per capita output growth over different horizons, this study makes one step further to close the gap between weather shocks and climate change, and assesses the macroeconomic effects of global warming. This article also adds to the existing literature by inspecting the underlying transmission mechanisms, both on the demand and the supply sides, and discussing the role of policy variables.

We show that in developing countries, sustained temperature deviations from their historical norms, *i.e.* global warming, negatively affects the growth rate of per capita real GDP. Our central estimate indicates that in the median country, a sustained 1°C increase in temperature deviations from their historical norms reduces the real

GDP per capita annual growth rate in 1.13 percentage points (0.74–1.52 percentage points, 90% confidence interval). Our results are robust to taking into account the level of develoment (countries below the 33rd percentile of the income distribution of the sample), excluding large carbon-emitting developing countries (China, India and Russia), controlling for commodity terms of trade, temperature and precipitation levels, and the occurrence of climate-related natural disasters, to including country-specific and common time trends, and to using real GDP growth as an alternative dependent variable.

Turning to the transmission mechanisms, we show that global warming shifts a share of aggregate demand from investment to consumption, possibly reflecting the salience of subsistence requirements in developing countries. Focusing on aggregate supply, we find that the relative importance of the industrial sector declines as the importance of agriculture grows, reinforcing the "food problem" in presence of subsistence requirements. Within the agricultural sector, while output growth declines, we also find evidence of a reallocation of resources towards short-term subsistence at the cost of future prosperity.

Finally, we have evidenced correlations between structural policy variables and the effect of global warming on per capita real GDP growth: higher levels of development appear to be related to lower macroeconomic damages from global warming. While this suggests that development policies might help foster resilience to climate change, least developed countries suffer the most since climate change has already made the implementation of such policies more challenging.

Overall, our results suggest that global warming threatens recent gains in the fight against poverty by making subsistence requirements more binding and represents a poverty trap, hindering further adaptation to climate change in developing countries. These impacts are particularly severe in low-income countries since they experience higher temperature increases than the average among developing countries and show more socioeconomic vulnerability and less resilience to economic shocks.

Our empirical estimates of the economic effects of global warming in developing countries call for a closer scrutiny of the calibration of developing countries’ damage functions in general equilibrium models. Future empirical research could use microeconomic data to provide evidences on the effectiveness of structural policies and allow for a causal interpretation of the relations between specific policies and the economic effects of global warming: a deeper and more precise understanding of these relations would help limit the increasing climate burden faced by countries the least equipped to face it.

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Appendix

A Country List, Classification and Data Sources

Table A.1 – List of Countries Included in the Main Regression Analysis

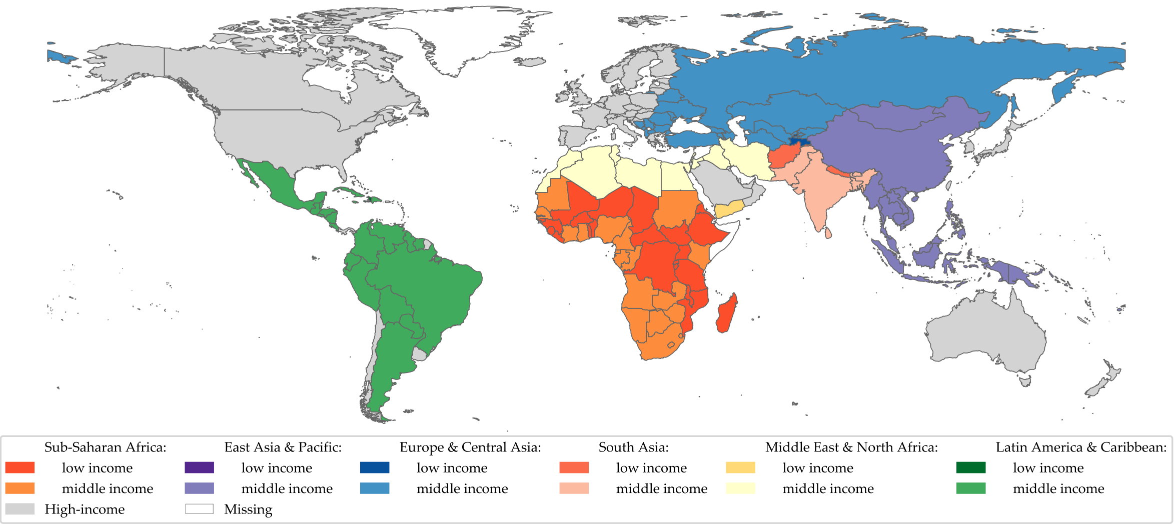
Low-Income Countries	Afghanistan, Benin, Burkina Faso, Burundi, Central African Republic, Chad, Democratic Republic of the Congo, Eritrea, Ethiopia, Gambia, Guinea, Guinea-Bissau, Haiti, Liberia, Madagascar, Malawi, Mali, Mozambique, Nepal, Niger, Rwanda, Sierra Leone, South Sudan, Tajikistan, Tanzania, Togo, Uganda, Yemen
Lower-Middle Income Countries	Angola, Bangladesh, Bhutan, Bolivia, Cambodia, Cameroon, Cape Verde, Comoros, Congo, Côte d'Ivoire, Egypt, El Salvador, Eswatini, Ghana, Honduras, India, Indonesia, Kenya, Kosovo, Kyrgyzstan, Lao, Lesotho, Mauritania, Moldova, Mongolia, Morocco, Myanmar, Nicaragua, Nigeria, Pakistan, Palestine (West Bank and Gaza), Papua New Guinea, Philippines, Sao Tome and Principe, Senegal, Solomon Islands, Sudan, Timor-Leste, Tunisia, Ukraine, Uzbekistan, Vanuatu, Viet Nam, Zambia, Zimbabwe
Upper-Middle Income Countries	Albania, Algeria, Argentina, Armenia, Azerbaijan, Belarus, Belize, Bosnia and Herzegovina, Botswana, Brazil, Bulgaria, China, Colombia, Costa Rica, Cuba, Dominica, Dominican Republic, Ecuador, Equatorial Guinea, Fiji, Gabon, Georgia, Grenada, Guatemala, Guyana, Iran, Iraq, Jamaica, Jordan, Kazakhstan, Lebanon, Libya, North Macedonia, Malaysia, Mauritius, Mexico, Montenegro, Namibia, Paraguay, Peru, Romania, Russia, Saint Lucia, Saint Vincent and the Grenadines, Samoa, Serbia, South Africa, Sri Lanka, Suriname, Thailand, Turkey, Turkmenistan, Venezuela

Note: the sample selection of middle- and low-income countries is exclusively based on data availability. Countries can be excluded either because no data for the GDP per capita are available in the WDI dataset, or because no climate data can be obtained from Matsuura and Willmott (2019).

Table A.2 – Data Sources

Variable:	Source:
Socio-Economic Variables:	
Real GDP per capita	World Bank - WDI (2019), and IMF–IFS
Sectoral Value Added (Services, Manufacturing, Industry)	World Bank - WDI (2019)
Agricultural data	USDA - ERS (2019)
Commodity Export Value	Gruss and Kebhaj (2019)
Human Development Index	UNDP - HDI (2019)
Climate Variables:	
Terrestrial Temperature and Precipitation	University of Delaware: Matsuura and Willmott (2019)
Natural Disasters	CRED - EM-DAT (2019)
CO_2 Emissions	Boden et al. (2017); Friedlingstein et al. (2019)

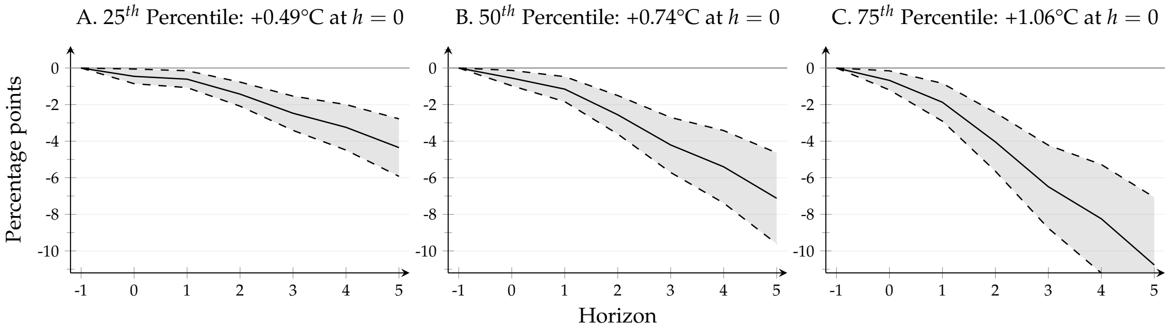
Figure A.1 – Country Classification



Source: The World Bank, elaborated by the authors. The classification corresponds to Fiscal Year 2020.

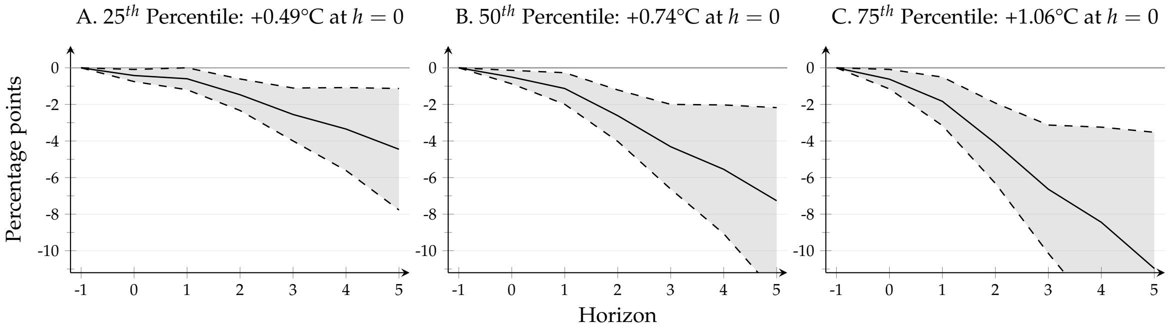
B Additional Results and Robustness Checks

Figure B.1 – Cumulative Effect of Temperatures Deviations from their Historical Norms on per Capita Real GDP, Excluding China, India and Russia



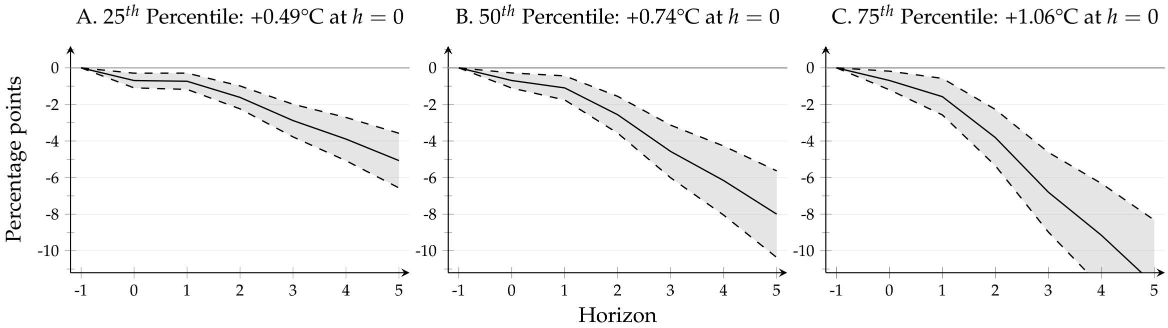
Note: The three panels show the cumulative response of per capita real GDP to a 1 °C increase in temperatures deviation from their historical norms excluding China, India and Russia from the sample. The distribution of these temperatures deviations refers to the difference in average mean temperature between the periods 2001–2017 and 1900–1950, shown in Figure 1. See Table 2 panel B for complete details on the values at each horizon.

Figure B.2 – Cumulative Effect of Temperatures Deviations from their Historical Norms on per Capita Real GDP, Driscoll-Kraay Standard Errors



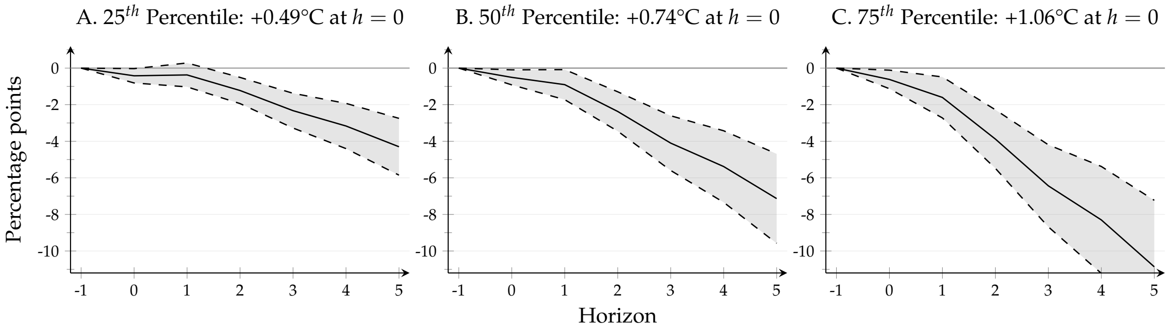
Note: The three panels show the cumulative response of per capita real GDP to a 1 °C increase in temperatures deviation from their historical norms using Driscoll and Kraay standard errors. The distribution of these temperatures deviations refers to the difference in average mean temperature between the periods 2001–2017 and 1900–1950, shown in Figure 1. See Table 2 panel B for complete details on the values at each horizon.

Figure B.3 – Cumulative Effect of Temperatures Deviations from their Historical Norms on per Capita Real GDP, Controlling for Commodity Exports Value



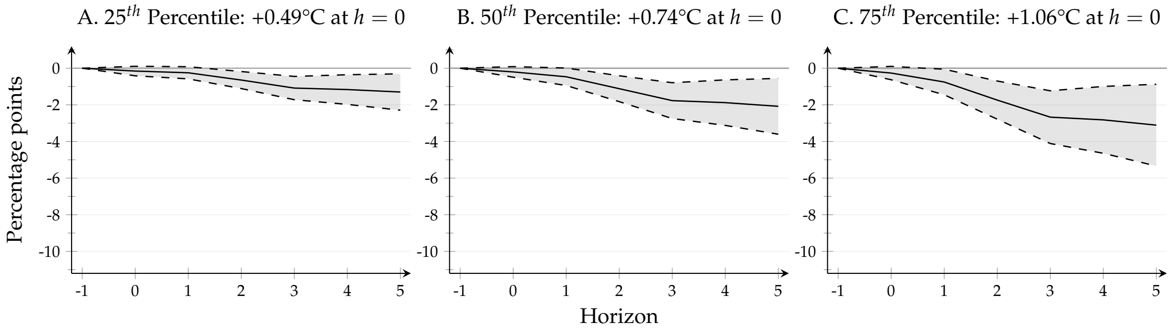
Note: The three panels show the cumulative response of per capita real GDP to a 1 °C increase in temperatures deviation from their historical norms controlling for commodity exports value. The distribution of these temperatures deviations refers to the difference in average mean temperature between the periods 2001–2017 and 1900–1950, shown in Figure 1. See Table 2 panel B for complete details on the values at each horizon.

Figure B.4 – Cumulative Effect of Temperatures Deviations from their Historical Norms on per Capita Real GDP, Controlling for Temperatures and Precipitations Levels



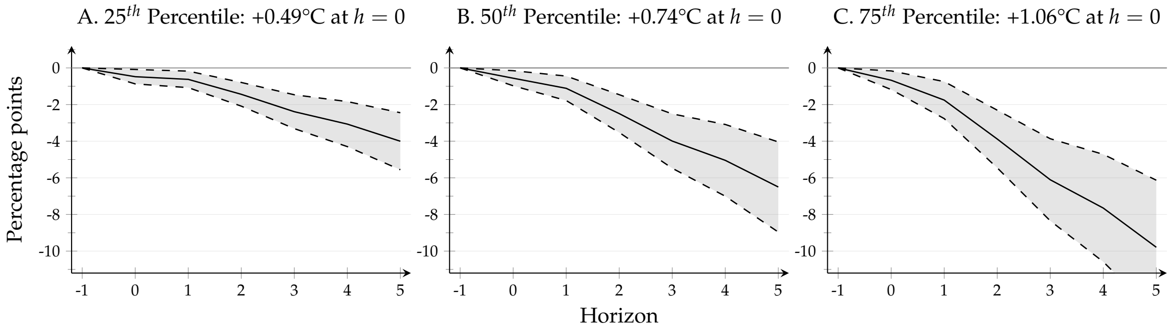
Note: The three panels show the cumulative response of per capita real GDP to a 1 °C increase in temperatures deviation from their historical norms controlling for temperature and precipitations levels. The distribution of these temperatures deviations refers to the difference in average mean temperature between the periods 2001–2017 and 1900–1950, shown in Figure 1. See Table 2 panel B for complete details on the values at each horizon.

Figure B.5 – Cumulative Effect of Temperatures Deviations from their Historical Norms on per Capita Real GDP, including High Income Countries



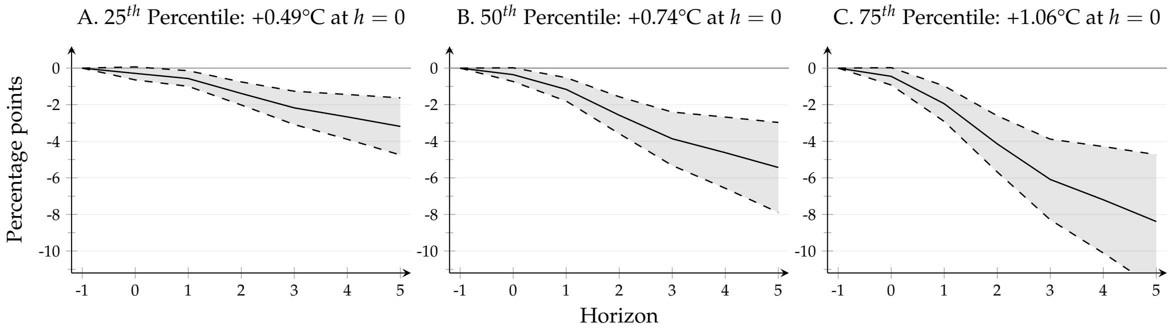
Note: The three panels show the cumulative response of per capita real GDP to a 1 °C increase in temperatures deviation from their historical norms including high income countries to the sample. The distribution of these temperatures deviations refers to the difference in average mean temperature between the periods 2001–2017 and 1900–1950, shown in Figure 1. See Table 2 panel B for complete details on the values at each horizon.

Figure B.6 – Cumulative Effect of Temperatures Deviations from their Historical Norms on Real GDP



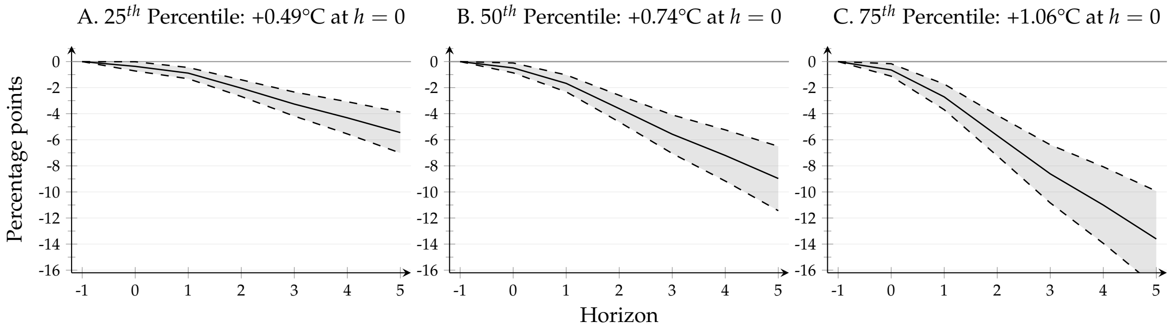
Note: The three panels show the cumulative response of real GDP to a 1 °C increase in temperatures deviation from their historical norms. The distribution of these temperatures deviations refers to the difference in average mean temperature between the periods 2001–2017 and 1900–1950, shown in Figure 1. See Table 2 panel B for complete details on the values at each horizon.

Figure B.7 – Cumulative Effect of Temperatures Deviations from their Historical Norms on per Capita Real GDP, Including a Linear Time Trend



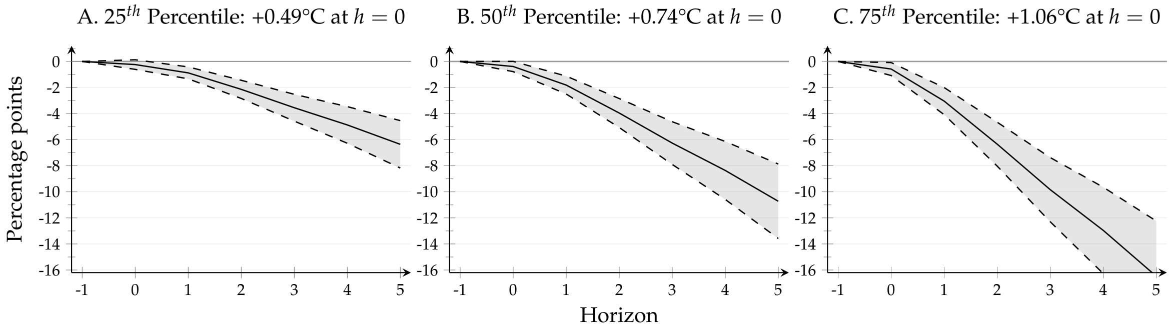
Note: The three panels show the cumulative response of per capita real GDP to a 1 °C increase in temperatures deviation from their historical norms, including a common linear time trend as control variable. The distribution of these temperatures deviations refers to the difference in average mean temperature between the periods 2001–2017 and 1900–1950, shown in Figure 1. See Table 2 panel B for complete details on the values at each horizon.

Figure B.8 – Cumulative Effect of Temperatures Deviations from their Historical Norms on per Capita Real GDP, Including a Linear and Quadratic Time Trends



Note: The three panels show the cumulative response of per capita real GDP to a 1 °C increase in temperatures deviation from their historical norms, including a common linear and quadratic time trends as control variables. The distribution of these temperatures deviations refers to the difference in average mean temperature between the periods 2001–2017 and 1900–1950, shown in Figure 1. See Table 2 panel B for complete details on the values at each horizon.

Figure B.9 – Cumulative Effect of Temperatures Deviations from their Historical Norms on per Capita Real GDP, Including a Country-Specific Linear Time Trend

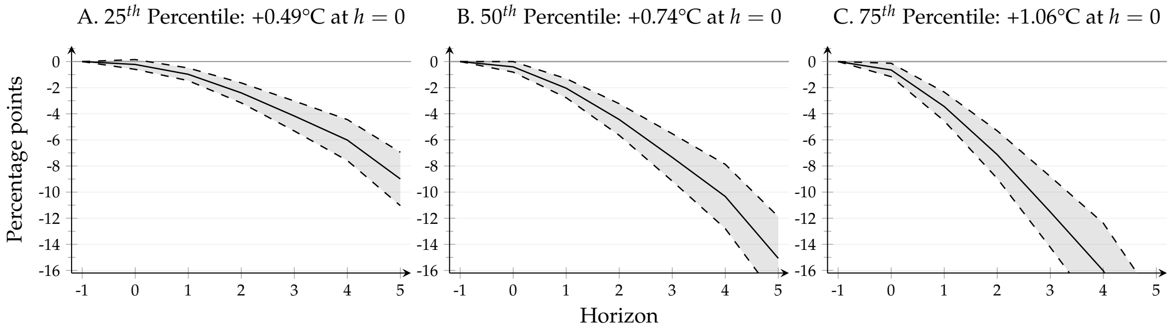

A. 25^{th} Percentile: +0.49°C at $h = 0$

B. 50^{th} Percentile: +0.74°C at $h = 0$

C. 75^{th} Percentile: +1.06°C at $h = 0$

Note: The three panels show the cumulative response of per capita real GDP to a 1 °C increase in temperatures deviation from their historical norms, including a country-specific linear time trend as control variable. The distribution of these temperatures deviations refers to the difference in average mean temperature between the periods 2001–2017 and 1900–1950, shown in Figure 1. See Table 2 panel B for complete details on the values at each horizon.

Figure B.10 – Cumulative Effect of Temperatures Deviations from their Historical Norms on per Capita Real GDP, Including a Country-Specific Linear and Quadratic Time Trends

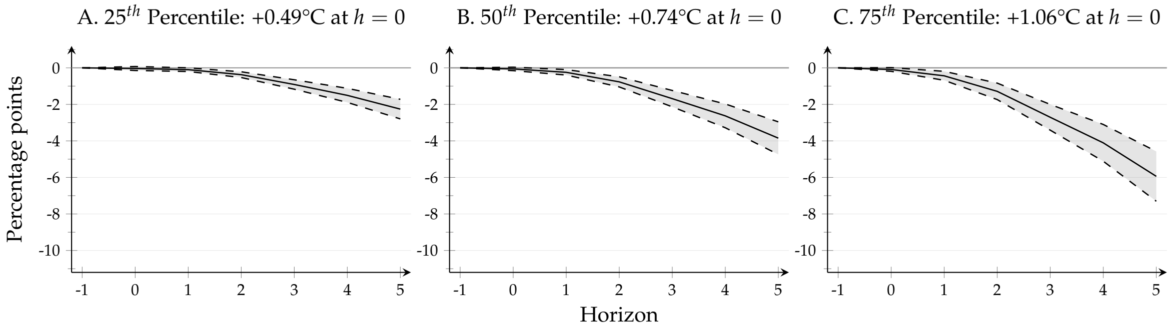

A. 25^{th} Percentile: +0.49°C at $h = 0$

B. 50^{th} Percentile: +0.74°C at $h = 0$

C. 75^{th} Percentile: +1.06°C at $h = 0$

Note: The three panels show the cumulative response of per capita real GDP to a 1 °C increase in temperatures deviation from their historical norms, including a country-specific linear and quadratic time trends as control variables. The distribution of these temperatures deviations refers to the difference in average mean temperature between the periods 2001–2017 and 1900–1950, shown in Figure 1. See Table 2 panel B for complete details on the values at each horizon.

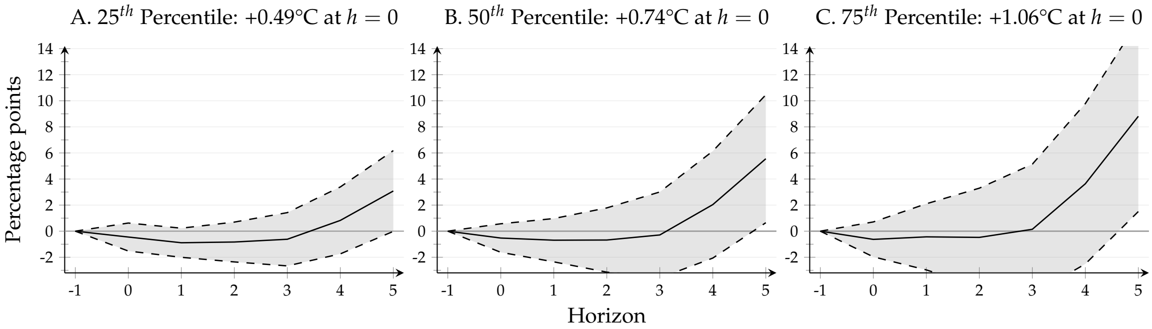
Figure B.11 – Cumulative Effect of Temperatures Deviations from their Historical Norms on Human Development Index



Note: The three panels show the cumulative response of the human development index to a 1 °C increase in temperatures deviation from their historical norms. The distribution of these temperatures deviations refers to the difference in average mean temperature between the periods 2001–2017 and 1900–1950, shown in Figure 1. See Table 2 panel B for complete details on the values at each horizon.

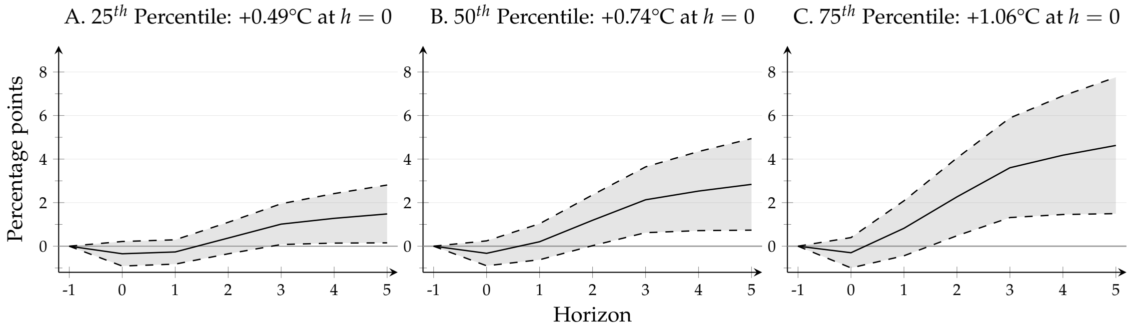
C Additional Transmission Channels

Figure C.1 – Cumulative Effect of Temperatures Deviations from their Historical Norms on Public Consumption


A. 25th Percentile: +0.49°C at $h = 0$ B. 50th Percentile: +0.74°C at $h = 0$ C. 75th Percentile: +1.06°C at $h = 0$

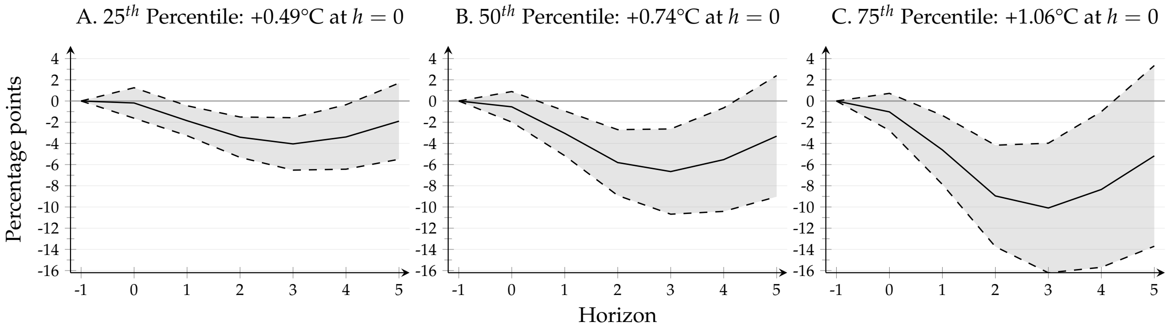
Note: The three panels show the cumulative response of the ratio of Public Consumption over GDP to a 1 °C increase in temperatures deviation from their historical norms. The distribution of these temperatures deviations refers to the difference in average mean temperature between the periods 2001–2017 and 1900–1950, shown in Figure 1. See Table 2 panel B for complete details on the values at each horizon.

Figure C.2 – Cumulative Effect of Temperatures Deviations from their Historical Norms on Total Consumption


A. 25th Percentile: +0.49°C at $h = 0$ B. 50th Percentile: +0.74°C at $h = 0$ C. 75th Percentile: +1.06°C at $h = 0$

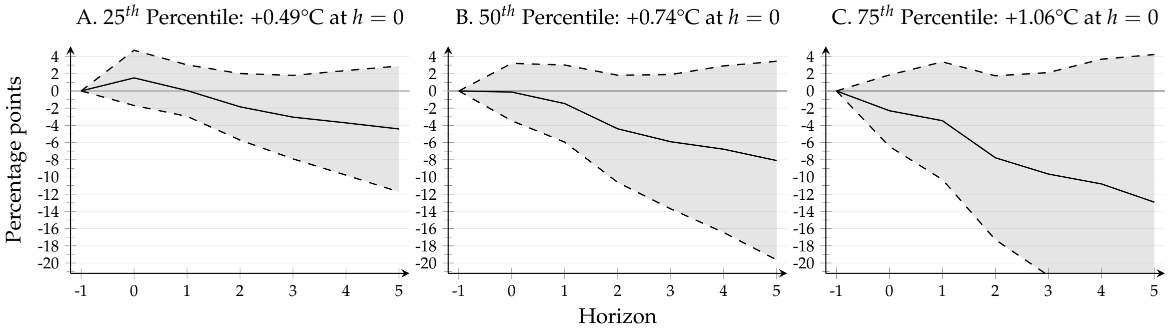
Note: The three panels show the cumulative response of the ratio of Public and Private Consumption over GDP to a 1 °C increase in temperatures deviation from their historical norms. The distribution of these temperatures deviations refers to the difference in average mean temperature between the periods 2001–2017 and 1900–1950, shown in Figure 1. See Table 2 panel B for complete details on the values at each horizon.

Figure C.3 – Cumulative Effect of Temperatures Deviations from their Historical Norms on Fixed Investment



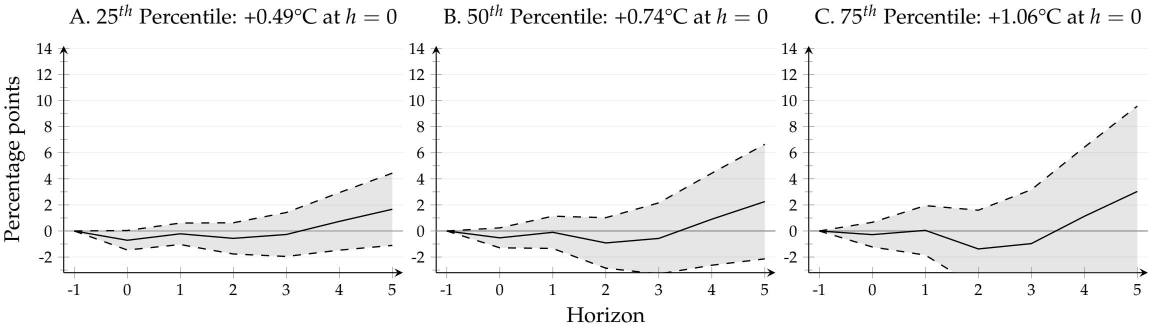
Note: The three panels show the cumulative response of the ratio of Fixed Investment over GDP to a 1 °C increase in temperatures deviation from their historical norms. The distribution of these temperatures deviations refers to the difference in average mean temperature between the periods 2001–2017 and 1900–1950, shown in Figure 1. See Table 2 panel B for complete details on the values at each horizon.

Figure C.4 – Cumulative Effect of Temperatures Deviations from their Historical Norms on Savings



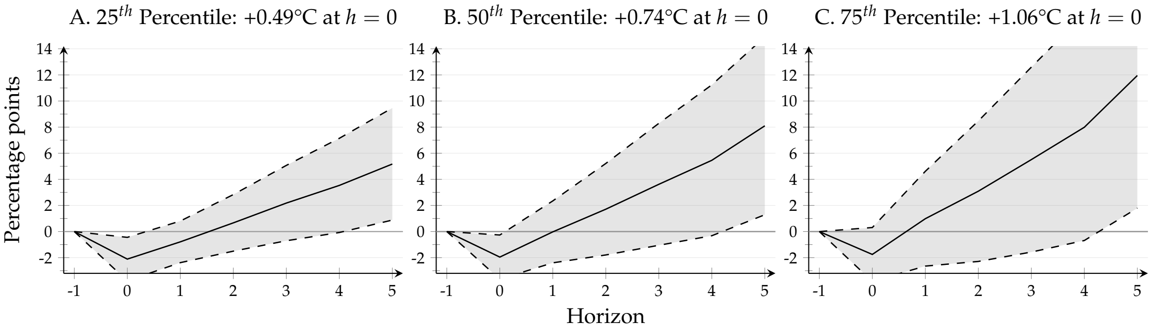
Note: The three panels show the cumulative response of the ratio of Savings over GDP to a 1 °C increase in temperatures deviation from their historical norms. The distribution of these temperatures deviations refers to the difference in average mean temperature between the periods 2001–2017 and 1900–1950, shown in Figure 1. See Table 2 panel B for complete details on the values at each horizon.

Figure C.5 – Cumulative Effect of Temperatures Deviations from their Historical Norms on Total Factor Productivity



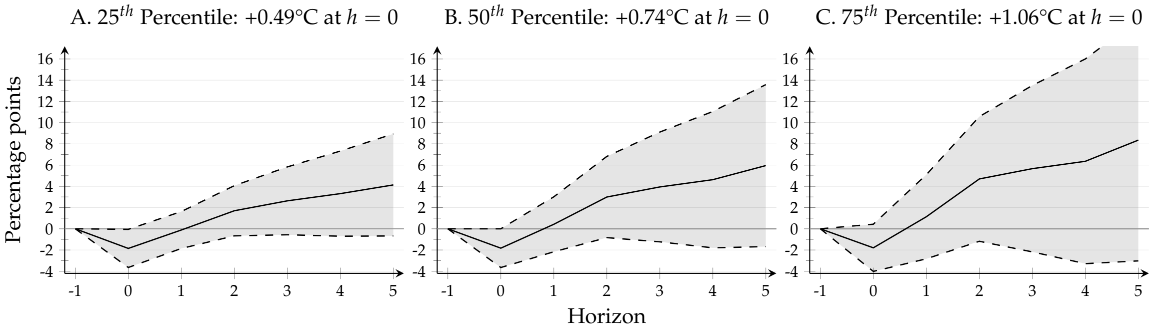
Note: The three panels show the cumulative response of Total Factor Productivity to a 1 °C increase in temperatures deviation from their historical norms. The distribution of these temperatures deviations refers to the difference in average mean temperature between the periods 2001–2017 and 1900–1950, shown in Figure 1. See Table 2 panel B for complete details on the values at each horizon.

Figure C.6 – Cumulative Effect of Temperatures Deviations from their Historical Norms on Imports



Note: The three panels show the cumulative response of the ratio of Imports over GDP to a 1 °C increase in temperatures deviation from their historical norms. The distribution of these temperatures deviations refers to the difference in average mean temperature between the periods 2001–2017 and 1900–1950, shown in Figure 1. See Table 2 panel B for complete details on the values at each horizon.

Figure C.7 – Cumulative Effect of Temperatures Deviations from their Historical Norms on Exports

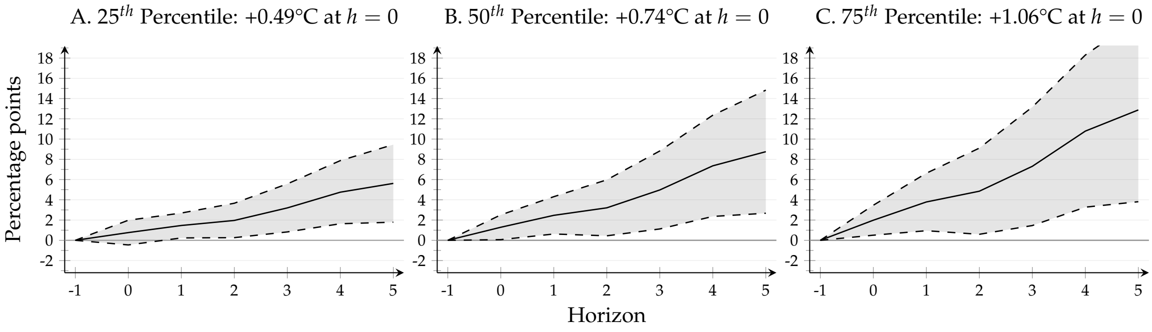

A. 25th Percentile: +0.49°C at $h = 0$

B. 50th Percentile: +0.74°C at $h = 0$

C. 75th Percentile: +1.06°C at $h = 0$

Note: The three panels show the cumulative response of the ratio of Exports over GDP to a 1 °C increase in temperatures deviation from their historical norms. The distribution of these temperatures deviations refers to the difference in average mean temperature between the periods 2001–2017 and 1900–1950, shown in Figure 1. See Table 2 panel B for complete details on the values at each horizon.

Figure C.8 – Cumulative Effect of Temperatures Deviations from their Historical Norms on Manufacturing Value Added

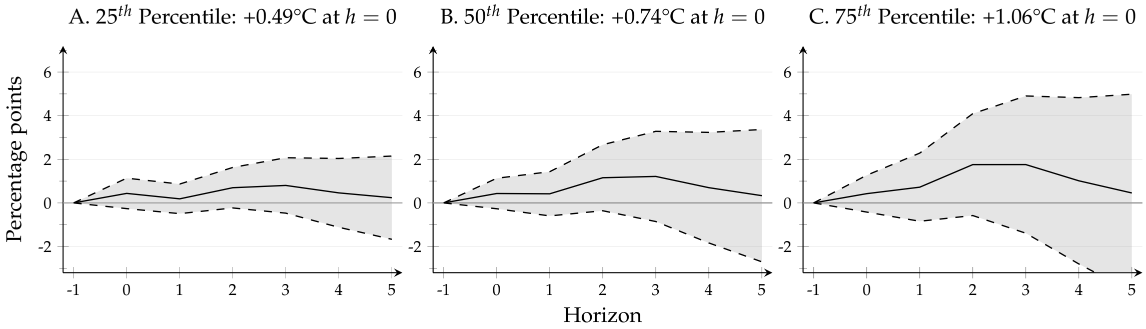

A. 25th Percentile: +0.49°C at $h = 0$

B. 50th Percentile: +0.74°C at $h = 0$

C. 75th Percentile: +1.06°C at $h = 0$

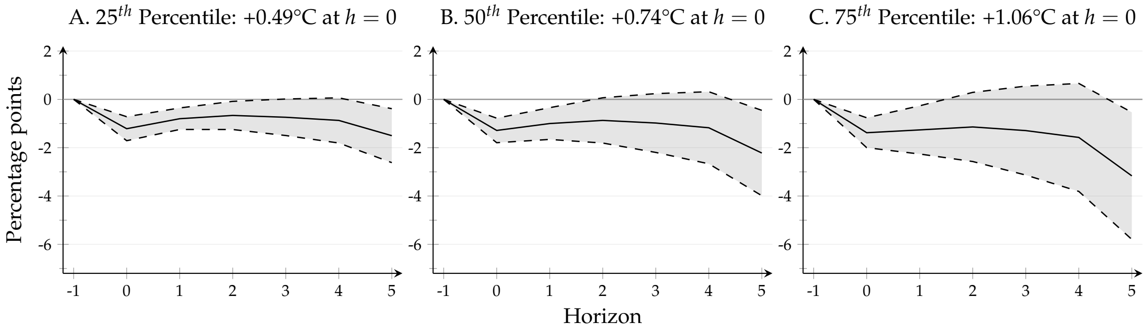
Note: The three panels show the cumulative response of the ratio of Manufacturing Value Added over GDP to a 1 °C increase in temperatures deviation from their historical norms. The distribution of these temperatures deviations refers to the difference in average mean temperature between the periods 2001–2017 and 1900–1950, shown in Figure 1. See Table 2 panel B for complete details on the values at each horizon.

Figure C.9 – Cumulative Effect of Temperatures Deviations from their Historical Norms on Services Value Added



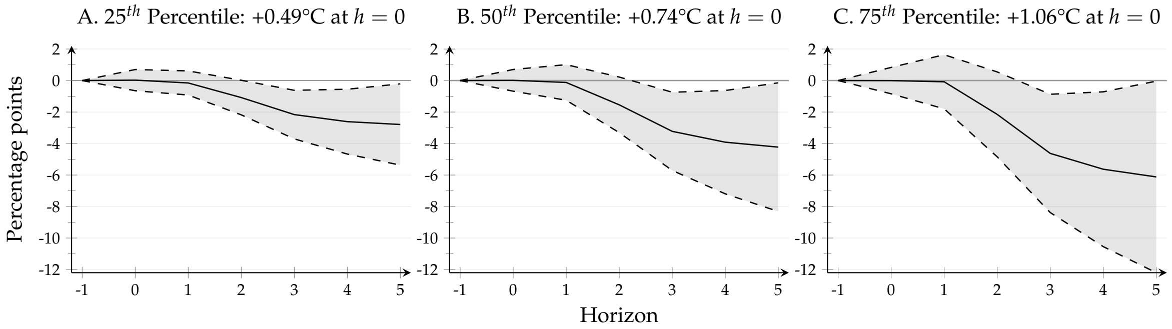
Note: The three panels show the cumulative response of the ratio of Services Value Added over GDP to a 1 °C increase in temperatures deviation from their historical norms. The distribution of these temperatures deviations refers to the difference in average mean temperature between the periods 2001–2017 and 1900–1950, shown in Figure 1. See Table 2 panel B for complete details on the values at each horizon.

Figure C.10 – Cumulative Effect of Temperatures Deviations from their Historical Norms on Agriculture Total Factor Productivity



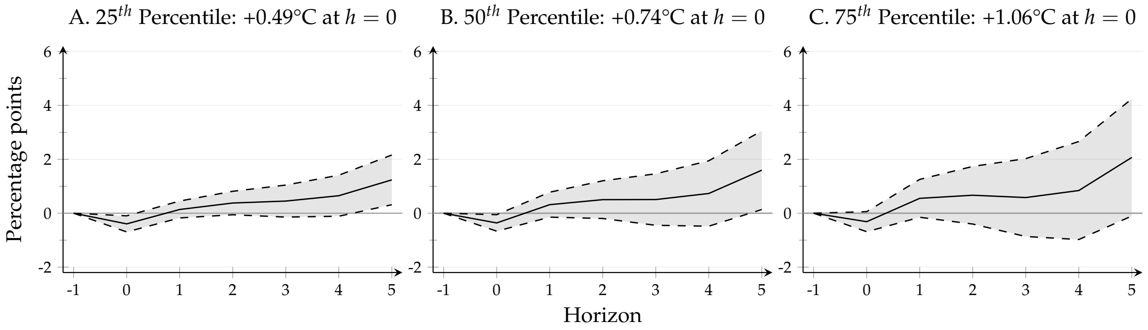
Note: The three panels show the cumulative response of Agriculture Total Factor Productivity to a 1 °C increase in temperatures deviation from their historical norms. The distribution of these temperatures deviations refers to the difference in average mean temperature between the periods 2001–2017 and 1900–1950, shown in Figure 1. See Table 2 panel B for complete details on the values at each horizon.

Figure C.11 – Cumulative Effect of Temperatures Deviations from their Historical Norms on Agricultural Machinery



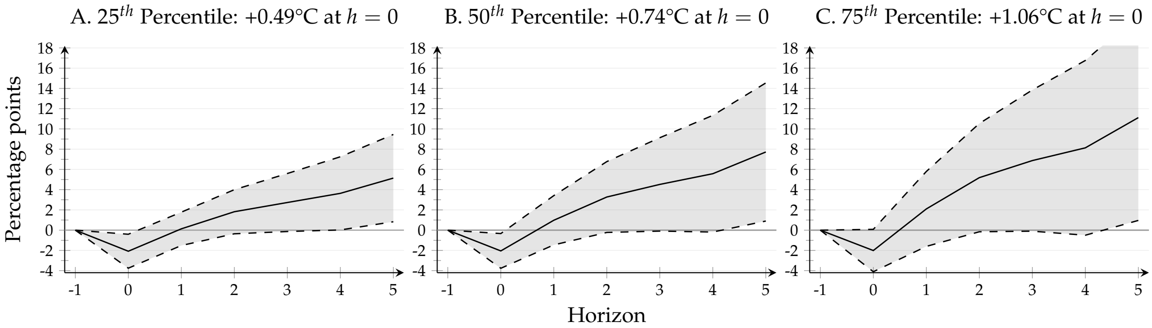
Note: The three panels show the cumulative response of Agricultural Machinery to a 1 °C increase in temperatures deviation from their historical norms. The distribution of these temperatures deviations refers to the difference in average mean temperature between the periods 2001–2017 and 1900–1950, shown in Figure 1. See Table 2 panel B for complete details on the values at each horizon.

Figure C.12 – Cumulative Effect of Temperatures Deviations from their Historical Norms on Agricultural Inputs



Note: The three panels show the cumulative response of Agricultural Inputs to a 1 °C increase in temperatures deviation from their historical norms. The distribution of these temperatures deviations refers to the difference in average mean temperature between the periods 2001–2017 and 1900–1950, shown in Figure 1. See Table 2 panel B for complete details on the values at each horizon.

Figure C.13 – Cumulative Effect of Temperatures Deviations from their Historical Norms on Fertilizers Use



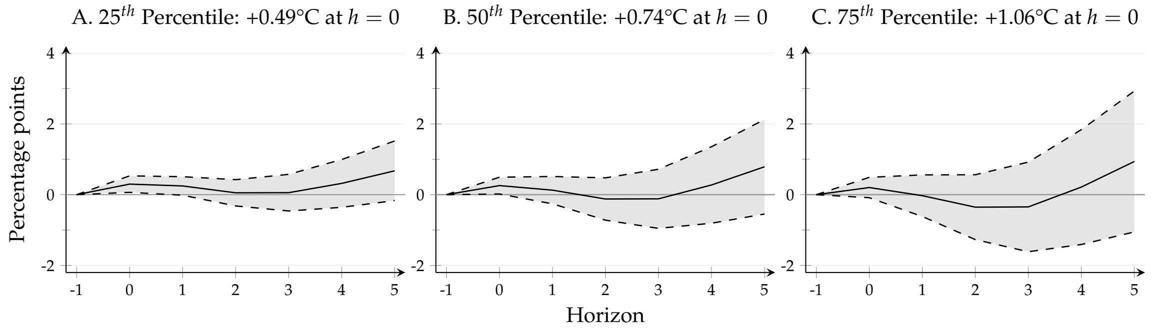
A. 25th Percentile: +0.49°C at $h = 0$

B. 50th Percentile: +0.74°C at $h = 0$

C. 75th Percentile: +1.06°C at $h = 0$

Note: The three panels show the cumulative response of Fertilizers quantity to a 1 °C increase in temperatures deviation from their historical norms. The distribution of these temperatures deviations refers to the difference in average mean temperature between the periods 2001–2017 and 1900–1950, shown in Figure 1. See Table 2 panel B for complete details on the values at each horizon.

Figure C.14 – Cumulative Effect of Temperatures Deviations from their Historical Norms on Agricultural Labour



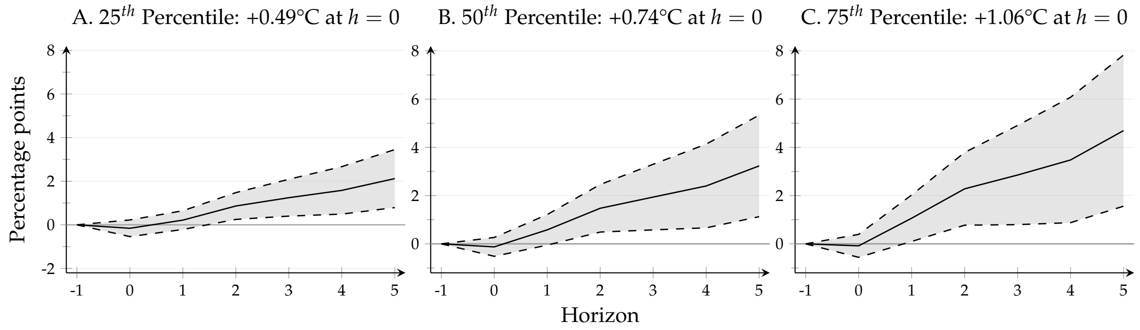
A. 25th Percentile: +0.49°C at $h = 0$

B. 50th Percentile: +0.74°C at $h = 0$

C. 75th Percentile: +1.06°C at $h = 0$

Note: The three panels show the cumulative response of Agricultural Labour to a 1 °C increase in temperatures deviation from their historical norms. The distribution of these temperatures deviations refers to the difference in average mean temperature between the periods 2001–2017 and 1900–1950, shown in Figure 1. See Table 2 panel B for complete details on the values at each horizon.

Figure C.15 – Cumulative Effect of Temperatures Deviations from their Historical Norms on Livestock


A. 25th Percentile: +0.49°C at $h = 0$

B. 50th Percentile: +0.74°C at $h = 0$

C. 75th Percentile: +1.06°C at $h = 0$

Note: The three panels show the cumulative response of Livestock to a 1 °C increase in temperatures deviation from their historical norms. The distribution of these temperatures deviations refers to the difference in average mean temperature between the periods 2001–2017 and 1900–1950, shown in Figure 1. See Table 2 panel B for complete details on the values at each horizon.

D Additional Policy Results

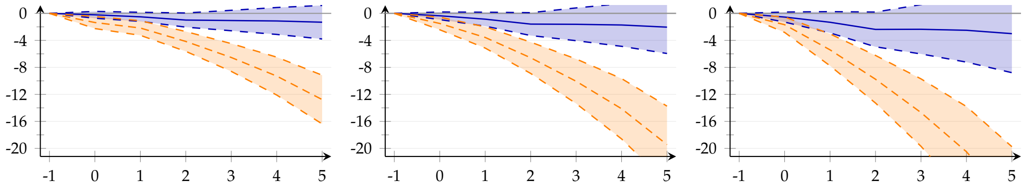
Figure D.1 – Cumulative Effect of Temperatures Deviations from their Historical Norms on per Capita Real GDP, According to Policy Levels

Panel A. Institutional Quality

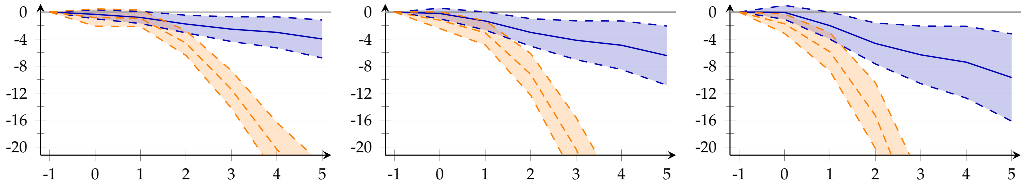
Column i.
25^{th} Percentile: +0.49°C at $h = 0$

Column ii.
50^{th} Percentile: +0.74°C at $h = 0$

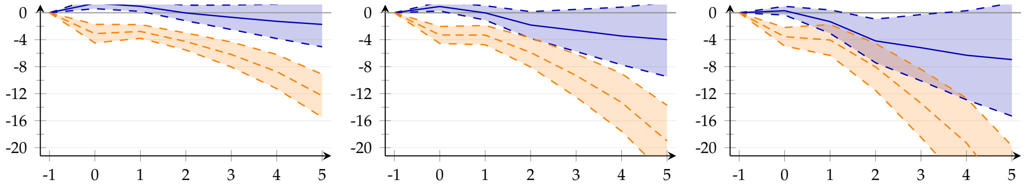
Column iii.
75^{th} Percentile: +1.06°C at $h = 0$



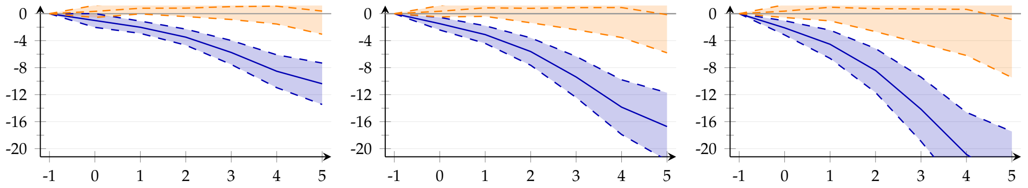
Panel B. Mobile Cellular Subscriptions



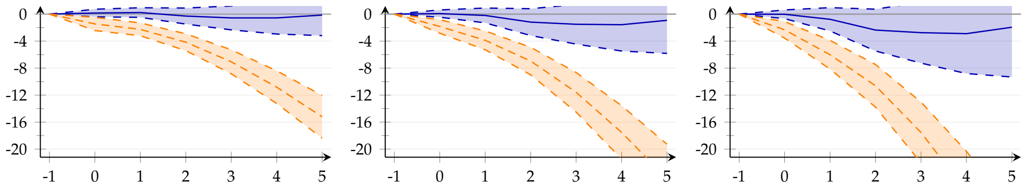
Panel C. Access to Electricity



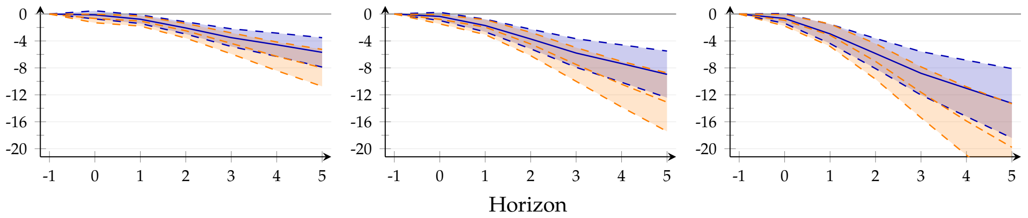
Panel D. Deforestation



Panel E. Coal Consumption



Panel F. De Facto Exchange Rate Regime



Note: Each panel shows the cumulative response of per capita real GDP to a 1 °C increase in temperatures deviation from their historical norms. The dark blue colour includes observations above the respective policy 75^{th} percentile, while the light orange colour includes observations below the 25^{th} percentile.