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The Macroeconomic Implications of Climate Change on Sub-Saharan Africa: A Case for Sustainable Development

Aydin Sandalli

Durham University Business School
e-mail: Aydin-Sandalli@hotmail.co.uk

"The biggest risk to African growth is climate change."
~ Paul Polman

Abstract
While climate change has harsh universal impacts, it is believed that its negative effects fall disproportionately on hotter, developing regions. This paper examines these claims using a panel datasets for 84 OECD and Sub-Saharan African countries between 1970–2018. I document both the evolution of country-specific temperatures and the long-term economic impact of temperature and precipitation variations on GDP per-capita. Using a panel auto-regressive distributed lag model on the sample mentioned above, I found that temperatures have unanimously increased for all sample-countries and that variations in temperature above historical norms significantly reduced income-growth. No significant relationship was found between precipitation and income growth. When interacting 'poor' and 'hot' country variables, I found that temperature variations disproportionately affected both hotter and poorer Sub-Saharan African countries. In OECD countries, temperatures have increased more quickly relative to their historical norms than Sub-Saharan African countries. Finally, while poorer and developing countries are more adversely affected by temperature variations, they seem to recover more quickly from temperature shocks than sample averages. I explain these results and link them to potential policy implications regarding global sustainable development and greenhouse gas abatement.
Keywords: Sub-Saharan Africa; OECD; climate change; GDP; greenhouse gas abatement; temperature variations
JEL Classification: C 33, O47, O50, Q20, Q54

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List of Abbreviations
SSA Sub-Saharan Africa
OECD Organisation for Economic Co-operation and Development
GDP Gross Domestic Product
ARDL Auto-regressive distributed lag
AIC Akaike information criterion
FE Fixed effects

Introduction

Climate change is arguably one of the most complex and daunting global challenges of our time (IPCC, 2007). Science is now unequivocal to the existence of climate change, yet, ascertaining its economic consequences prove far more difficult (Tenkate et al., 2009). The most notable feature of climate change has been unprecedented increases in global average temperatures. Evidence suggests that the global average temperature has increased roughly 1 °C in the last 140-years, with a substantial acceleration in the rate-of-temperature-increase in the last 30-years following a spike in anthropogenic greenhouse gas (GHG) emissions (IPCC, 2014; Kompas, Pham & Che, 2018). Worryingly, without any mitigation policies, forecasts threaten a further 3–5 °C increase in global temperatures by 2100, with potentially drastic consequences on human enterprise (Hertel, Burke & Lobell, 2010; Avecedo et al., 2018).

However, rising temperatures are only part of the problem. Recent years have witnessed surges in extreme weather events, including droughts, floods, heatwaves, and cold snaps. Climate variability can cause severe long-term macroeconomic impacts through changes in precipitation patterns, rising sea-levels, and extreme-weather volatility (World Bank, 2016; United Nations, 2018). Consequently, these climate variations may adversely affect the global economy by reducing agricultural output, slowing investment, and damaging human health with the increased spread of disease and tougher working environments (Stern, 2007; Kahn et al., 2019).

While these distributional changes in weather patterns have harsh universal impacts, it is postulated that the burden of climate change falls disproportionately on hotter, low-income countries (Tol, 2009; Dell, Jones & Olken, 2012; Burke, Hsian & Miguel, 2015a). A particular focus of the literature has been on Sub-Saharan Africa (SSA) due to its unforgiving geographic exposure, dependence on climate-sensitive agricultural sectors and low-income, all weakening its capacity to technologically adapt to climate change (Abidoye & Odusola, 2015). Contemporary literature suggests hotter countries tend to be poorer — reducing their ability to adapt to weather shocks with national income falling 8.5 per cent per-degree Celsius (Dell, Jones, and Olken 2009). Moreover, the economic landscape of SSA makes it particularly vulnerable as economic performance in agriculture, forestry, tourism, energy, and coastal services are all dependent on climate dynamics, exacerbating any impact climate variability has on economic growth (Fankhauser, 1995; Boko et al., 2007). Furthermore, the geographical location of SSA falls on lower latitudes, where nearly 80 per cent of all climate-related damages are concentrated (Mendelsohn, 2008).

The broad consensus among scientists is that climate change is affected by the concentration of GHG's in the atmosphere, with recent anthropogenic contributions widely recognised as the driving factor accelerating climate change (Eboli et al., 2010; IPCC, 2014; Brown et al., 2016). Yet, while SSA contributes some of the smallest proportions of global GHG emissions at less than 5 per cent of the total carbon output, it bears disproportionate adverse effects of climate change (Rehdanz & Maddison, 2003; Mendelsohn et al., 2006; UNDP, 2006; Tol 2009).

What makes matters worse is the continued need for economic growth and development in SSA, given its relatively low GDP per-capita compared to global averages (World Bank, 2020). However, increased energy consumption, accompanied by large-scale rural-urban migration, population increases, agricultural intensification and urbanisation necessary for SSA's economic development, has been adduced as the largest contributor towards GHG-emissions (Martinez-Zarzoso & Maruotti, 2011). With knowledge of the already substantial temperature rises between 1–3 °C in SSA over the past 50-years and the forecasts that further increases in GHG-concentrations will likely increase weather-extremes (Diffenbaugh Ahmed and Hertel, 2009), there is a need to not only understand what the previous impacts of climate change have been on SSA relative to other, developed countries, but also what policies can be put in place by both developed and developing countries to foster global co-operation towards sustainable economic development. By understanding climate variable dynamics, their country-specific heterogeneous impacts on economic growth, and whether these climate variations have regional asymmetry in effects, policymakers can better introduce schemes to abate GHG-emissions.

However, there is a dearth of econometric literature analysing the aggregate and country-specific effects of climate change on SSA. The literature predominantly documents the continental or aggregate effects of climate change on countries' clusters (Burke, Hsiang, & Miguel, 2015a; Avecedo et al., 2018). By doing this, they fail to capture heterogeneous effects of climate variations both within and between countries. Moreover, previous studies tend to focus on the short-term effects of climate change rather than its long-term impacts on growth (Stern, 2007; Cashin et al., 2017). Consequently, they fail to analyse whether climate change has persistent lagged-effects on economic growth, and if so, how long these lagged-effects last. Additionally, much of the literature focuses on cross-sectional approaches (Sachs & Warner, 1997; Nordhaus, 2006); thus, neglecting the potential relationship between countries economic growth and climate change over time. It is particularly problematic as it is subject to endogeneity given the possible feedback-effects and interactions between climate variables and GDP-growth.

Furthermore, methodological issues regarding econometric specifications are pervasive in the literature exploring climate change and economic growth. Most studies adopt the temperature level as a variable, rather than utilising deviation from temperature relative to historical norms (Dell, Jones, & Olken, 2012; Burke, Hsiang, & Miguel, 2015a). As the temperature-level is a trended variable, inclusion as a regressor produces quadratic trends between temperature and log GDP per-capita growth — which can bias estimates (Kahn et al., 2019). While some recent papers tackle some of the issues mentioned above, they either fail to compare SSA to the other countries, important when claiming SSA is worse off than more developed economies (Abidoye & Odusola, 2015), specify arbitrary lag-lengths that fail to recognise the extent of climate variations impact on economic growth and how it fluctuates over multiple lagged-years (Kahn et al., 2019), or use outdated datasets that fail to encapsulate the effects of sharper climate variations seen in the last decade.

Henceforth, this paper looks to fill some of the gaps in the literature. Using a panel auto-regressive distributional lag (ARDL) model, I first measure country-specific annual temperature changes for a set of 84 OECD and SSA countries between 1970–2018. Implementing a panel ARDL model allows for significant heterogeneity between-countries concerning temperature changes over time, permitting better comparisons of country-specific climate variations. Next, I analyse the long-term economic impacts of climate change on log per-capita growth using a panel ARDL model for the 84-country sample over an updated time-horizon between 1970–2018. Lag-lengths are specified using an Akaike information criterion (AIC) to better model the long-run lagged-effects climate change may have on growth over multiple years.

Moreover, using a panel ARDL allows for long-run dynamics and bi-directional feedback effects, better modelling the interactions between climate variables and per-capita growth over-time. This specification also overcomes problems with endogeneity and allows for heterogeneous effects of climate change on per-country economic growth, seldom documented in the literature. The current paper also adopts the use of temperature variations relative to historical norms instead of absolute temperature values, allowing for non-linearity that combats the econometric drawbacks of using trended variables. Ultimately, I conclude by linking results to policy implications for sustainable development.

Literature Review

Given the spur in popularity concerning the climate change debate in recent years, there is a burgeoning attempt to quantify climate change's effects on economic growth. Novel approaches either attempt to document the previous impact climate change has had over the last century (Dell, Jones, & Olken, 2012; Avecedo et al., 2018; Kahn et al., 2019) or forecast future implications of climate change subject to different abatement strategies (Nordhaus & Yang, 1996; Weitzman, 2012; Nordhaus, 2013; Dietz & Stern, 2014; Wade & Jennings, 2016). While both avenues offer useful insights into climate-policy, a greater focus will be given to reviewing the literature regarding the previous effects climate change has had on economic growth rates. Therefore, I can better determine how climate change engenders detriment to growth through its macroeconomic and microeconomic implications and if climate change has asymmetric effects on different regions.

Previous studies focus on how climate change impacts growth through two-dimensions. Firstly, macroeconomic studies subject the adversities of climate change through its influence on agricultural output, crop yields, commodity prices, investment, and institutions (Pindyck, 2011; Dell, Jones, & Olken, 2012; Ignjacevic et al., 2020). Secondly, microeconomic analysis attributes falling growth-rates to an array of factors including physical and cognitive labour productivity, disease, conflict, and political instability (Brückner & Ciccone, 2011; Dell, Jones, & Olken, 2014; Hsiang & Neidell, 2015; Somanathan et al., 2017). I aim to give a brief overview of the literature suggesting climate change has negatively impacted growth, particularly in developing countries. Moreover, I offer possible macroeconomic and microeconomic explanations for these findings based on the literature.

Adverse Temperature Impacts on Developing Countries

While papers are unambiguous to the negative effects of climate change on global economic growth, a nascent trend of articles have evidenced the asymmetric impact climate change has on developing countries. From a panel of 180-economies utilising Jordà's (2005) shock projection impulse-response function, Avecedo et al. (2018) found that annual temperature variations have uneven short-term and long-term macroeconomic effects on low-income countries and countries concentrated in hotter regions. In particular, for the median developing country with an average temperature of 22 °C, each additional 1 °C above this average decreases growth by 0.9 per cent annually, however, for even hotter developing countries with an average temperature of 25 °C, a further 1 °C increase lowers growth by 1.2 per cent annually. Furthermore, the cumulative impacts were noted 7-years after the initial weather shock, with per-capita outputs remaining 1 per cent lower for emerging-economies, and 1.5 per cent lower for low-income economies. These results suggest that developing countries are more adversely affected by temperature variations and that they struggle to recover from long-term adverse temperature shocks.

Seminal contributions have also offered similar results. In a global panel spanning 136-countries between 1950–2003, Dell, Jones and Olken (2012) found that higher temperatures have significant, negative impacts on economic growth, but only in developing countries. The authors find that a 1 °C increase in temperature reduced economic growth for the same year by 1.3 per cent. Moreover, they found that the temperature shock had significant lagged effects that were not reversed after the initial shock subdued. Dell et al. (2012) claim that temperature increases have substantial long-run effects on both the output and growth potential of low-income countries but find no robust evidence for developed economies. Similarly, Bansal and Ochoa (2011) examined the relationship between global temperature changes (contrasting to country-specific changes) and economic growth. They find that a 1 °C global average temperature increase reduces growth by roughly 0.9 per cent annually, with the most substantial growth reductions in poorer countries located closer to the equator.

These results are corroborated mainly by Burke, Hsiang, and Miguel (2015a). Using a panel dataset of 166-countries between 1960–2010, Burke et al. (2015a) compare the country's economic production with itself over different time-periods, contrasting between when the countries average temperature is hotter and alternatively when cooler. The authors find that economic production peaks at an average annual temperature of 13 °C, with output, strongly declining at higher temperatures, offering these findings an explanation for labour productivity and economic-output differentials between developed and developing countries be hotter.

However, Dell et al. (2012), Burke et al. (2015a), and Bansal and Ochoa's (2011) studies all suffer methodological issues regarding their econometric specification of climate variables. Using trended climate variables such as temperature level instead of temperature variations relative to historical averages, results including temperature-levels as a regressor produce quadratic (or linear for non-logged per-capita growth) trends in log per-capita growth that may bias their estimates. Moreover, Bansal and Ochoa's (2011) study fails to capture climate change's heterogeneous effect. They regress global average temperature shocks instead of country-specific climate shocks and their influence on their economic growth. By neglecting heterogeneity, they assume that all countries, never mind regions within countries, have the same climate variations and react homogeneously, which may not be the case.

As mentioned above, the literature focuses on larger panels studying climate effects globally. They often fail to capture the diverse impact climate change has on other specific countries or regions, particularly SSA. Therefore, it is important to review literature focused on developing countries and regions to identify any regional disparities between countries. Using annual data for 34-countries in SSA between 1961–2009, Abidoye and Odusola (2015) sought to identify climate change's impact, particularly climate variation, on economic growth. They found a significant, negative impact of climate change on economic growth-rates, deducing that a 1 °C increase in temperature above its average reduces GDP growth in SSA by 0.67 per cent annually. They also conduct sensitivity analysis on the individual impact of climate change per-country, finding that the two larger and more developed economies of Nigeria and South Africa greatly ameliorate the even more severe impacts on poorer African nations. Analogous results are found in country-specific estimates with Ali (2012) who used co-integration analysis on Ethiopia to see that economic growth is significantly reduced following changes in climate variables' magnitude and variability.

Moreover, similar results to those found in SSA were also substantiated in other developing regions. Using a panel of 67 countries comparing developed and developing countries, Rehdanz and Maddison (2005) found that a 1 per cent increase in temperature leads to a 0.4 per cent decrease in global GDP, but with a much more detrimental 23.5 per cent GDP reduction in developing countries. Similarly, when comparing highly vulnerable regions across SSA and South-East Asia, higher temperatures were associated with an increased prevalence in extreme weather patterns such as droughts and flooding, significantly damaging the emerging economies (Mendelsohn et al., 2006). Ahmed, Diffenbaugh, and Hertel (2009) concur with these findings, demonstrating implementation of a novel economic-climate analysis framework on 16-developing countries that climate volatility and temperature changes drastically increased poverty rates, particularly on urban-wage earners in SSA.

Contrarily, not all contemporary literature has found asymmetric impacts on developing countries' climate change effects. Using a panel ARDL model on a set of 174-countries between 1960–2014, Kahn et al. (2019) found that long-run per-capita growth was negatively influenced across all countries following temperature variations from their historical norms, with a 0.01 °C annual temperature deviation above or below historical norms lowering income growth by 0.0543 per cent. Controversially, no significant evidence was found for disproportional, negative impacts of climate variations on hotter or lower-income countries.

There is a large disparity between the absolute growth-reduction estimates between studies ranging from 0.4–23.5 per cent per 1 °C temperature increase. Still, there are some discrepancies between the existence of unequal impacts of climate change amongst developed and developing countries. Additionally, the literature often fails to appropriately capture the lagged impact of climate change on economic growth. Studies either neglect the use of lagged-effects entirely (Abidoye & Odusola, 2015) or use capricious lag-lengths that fail to encapsulate the persistent or variable changes in a countries' response over multiple lagged-years following a climate shock (Kahn et al., 2019).

Precipitation

So far, I have focused predominantly on the literature classifying the effects of temperature variability on economic growth. Yet, much of the literature is focused on factors exacerbated by variations in annual precipitation-rates. Considering the differential effects of temperature and precipitation deviations from historical norms between SSA and non-African countries, Barrios, Bertinelli, and Strobl (2010) focused on increased rainfall's income effects between 1960–1990. They found that increased rainfall is associated with faster income-growth in SSA, but not elsewhere. In fact, they suggest that declining rainfall conditions in SSA can explain 15–40 per cent of the per-capita income disparities between SSA and the rest of the developing world.

Similar results are demonstrated by Miguel, Satyanath, and Sergenti's (2004) analysis of 41 African-countries between 1981–1999. They found that both current and lagged precipitation growth-rates positively predict annual per-capita growth. Moreover, their follow-up study found that the same sample showed similarly positive income effects from current and lagged precipitation increases (as opposed to growth) (Miguel & Satyanath, 2011). Reinforcing this relationship, Bruckner, and Ciccone (2011) found that negative rainfall shocks significantly lowered income-levels in SSA. Studies focused on individual African countries show similar effects, with Ali's (2012) Ethiopian cointegration analysis finding large, adverse effects of changes in rainfall magnitude and variability on income-growth and long-run agricultural output levels.

However, while several studies document the significance of precipitation variations on income growth, an equal number fails to find any significant relationship between the two. Even Miguel and Satyanath's (2011) study found that the association between precipitation variation and income-growth became weak after the year-2000. Moreover, while Dell et al.'s (2012) study mentioned above found that general precipitation has positive influences on agricultural output in developing countries, variations in precipitation-rates have little effect on national growth in both developed and developing countries. These results were also concluded in their earlier study finding that average precipitation levels have no impact on growth between or within sample-countries (Dell, Jones, & Olken, 2009).

Contemporaneous studies also contend with the earlier literature, with both Avecedo et al. (2018) and Kahn et al.'s (2019) large panel datasets obtaining no statistical evidence that persistent precipitation changes above or below historical norms between 1960–2014 have any significant impact on per-capita growth rates. The authors argue that no robust relationship has been found due to potential measurement errors when collating precipitation variables. Auffhammer et al. (2011) suggest that temporal aggregation of precipitation variables bias results, therefore collecting data during a crop's growing season offers a better understanding of the effects of precipitation on economic growth.

Avenues of Impact

So far, I have reviewed literature specific to the impact of climate change variables on income-growth, particularly in SSA and other developing countries. However, I believe it is essential to review the microeconomic and macroeconomic avenues through which climate change may detriment developing economies. However, given the multitude of potential avenues in which climate variables can impact economic growth, the following review will be brief and not exhaustive.

With a clear relationship between agricultural yields and the environment, it is obvious why much of the literature has focused on the effects of climate variations on agricultural productivity. As the climate becomes more extreme, droughts become more frequent and thus, crop-yields fall (Wade & Jennings, 2016). Declining crop-yields increase global food-prices; however, these effects are exacerbated for low-income countries with a higher proportion of income devoted to food-items (Hallegatte et al., 2016; Hallegatte & Rozenberg, 2017). Thus, climate variations are theorised to particularly impact developing countries such as SSA that bare hotter temperatures and depend more on agricultural output (Toi & Yohe, 2007b).

Schlenker and Lobell (2010) used a panel of developing countries to estimate the impact of weather fluctuations on a model of yield-responses. They found that higher temperatures and increased temperature variations largely reduce crop-yields, particularly in SSA. Similar results are found across the developing world, with Guiteras (2009) finding that temperature increases reduce India's agricultural output. Welch et al. (2010) interestingly deduce that increases in minimum temperatures reduce agricultural output, whereas higher maximum temperatures seem to increase agricultural output. While similar results were found in other South-Asian countries (Levine & Yang, 2006), rising temperatures are often more drastic on SSA-yields than other developing countries. Barrios et al. (2008) found that rising temperatures were more severe in SSA, suggesting that had climate variations remained similar across the entire developing world, SSA would only be 32% of their current income-gap deficit with other developing economies.

However, much of the agricultural output climate change nexus is focused on temperature influences on crop yields, rather than precipitation. While studies do exist and suggest that negative rainfall variations and precipitation shocks adversely impact crop-yields, the literature is sparse and usually focused on single-country estimates in South-Asia (Jayachandran, 2006; Yang & Choi, 2007). There is a disconnect between theory and quantitative empirics. While most literature is consistent, linking temperature effects, agricultural yields, and their impact on income growth — it is difficult to say the same for precipitation studies. There is no robust evidence that precipitation effects income-growth, and limited proof that precipitation impacts agricultural output.

Finally, other microeconomic avenues in which climate change may affect developing countries disproportionately include through the spread of disease and health-linkages (Tanser et al., 2003; Deschênes & Greenstone, 2011), conflict and political instability (Burke et al., 2009; Fjelde & von Uexkull, 2012; Harari & La Ferrara, 2013) and labour productivity (Lundgreen et al., 2012). For example, Burke et al. (2015a) found that economic-productivity peaks at an annual temperature of 13 °C, with strong productivity declines at higher temperatures. Moreover, evidence from surveys based on laboratory experiments suggests that heat exposure beyond a certain point significantly reduces performance on cognitive and physical tasks. Seppänen, Fisk, and Faulkner (2003) report that productivity reduces by 2 per cent for every 1 °C temperature increase above 25 °C. In a later paper, they accentuate these claims suggesting that temperatures between 23 ºC and 30 ºC reduce productivity by 9 per cent. Most importantly, Graff, Zivin, and Neidell (2014) extrapolate these claims to hot, developing countries. When classifying sectors as 'heat-exposed' or not, the authors find productivity in 'heat-exposed' industries significantly reduced compared to non-heat-exposed sectors.

Ultimately, there is clearly macroeconomic and microeconomic avenues in which climate change may hinder income growth, particularly for SSA and other developing countries. However, while there is some consistency in results for the effect temperature variation has on economic growth, results are not-robust as clear methodological issues need addressing for much of the literature. For the role of precipitation changes on growth, results are inconclusive and lack clarity in their channels of impact. Finally, given the steep-rise in global GHG emissions in the past decade, the literature needs to be updated to predict better the impact of more recent climate variations on economic growth.

Data

Dataset and variables

The previous predictions that climate change impacts economic growth adversely in SSA are tested using an unbalanced cross-country panel dataset of GDP per-capita and the deviations of temperature and precipitation from their historical norms between 1970 and 2018. Data was gathered for 84-countries in total, including all 37-OECD and 47-SSA countries. Réunion and Western Sahara were omitted from the panel due to data scarcity. I chose SSA as it theorised to have particularly adverse responses to climate change, while also being a region that is agriculturally oriented in output and particularly poor relative to global averages (Hallegatte & Rozenberg, 2017). OECD countries are used as a comparison as they are predominantly focused on more temperate climates with more developed economies, with theorists suggesting that climate change may have a less substantial, or even positive impact on their economic growth (Mendelsohn, Schlesinger, & Williams, 2000; Dell, Jones, & Olken, 2012).

Temperature anomalies for each country were obtained through the Global Historical Climatology Network-Monthly (GHCN-M) and the International Comprehensive Ocean-Atmosphere Data Set provided by the National Oceanic and Atmospheric Administration. The time series, produced by Smith et al. (2008), contains updated monthly average temperature anomalies on a 0.5-degree by 0.5-degree resolution grid with a blended average across land and ocean surfaces. The current study utilises yearly averaged data from January to December between 1970–2018 as other panel variables are less complete across greater temporal scales that may further unbalance the panel. Moreover, this period allows us to clearly interpret climate changes over the last half-century, alongside GHG-emissions' noticeable rise throughout the last 50-years. The panel is rich in its time dimension (T) with $T = 48$ for all cross-sectional (N) observations of $N = 84$ countries.

Temperature anomalies classified in this sample as temperature deviations (degrees Celsius) from historical norms using 1981–2010 as historical averages are used as a reference instead of trended temperature variables. Temperature anomalies better encapsulate both positive and negative influences of deviations above and below historical norms, allowing for nonlinearity in climate variables' impact on labour productivity and growth. It overcomes problems with much of the literature that only analyses trended temperature values, inducing linear trends in per-capita output which may bias growth-equation estimates (Dell, Jones, & Olken, 2012; Burke, Hsiang, & Miguel, 2015a). Thus, the current study analyses temperature changes over time and its relative temperature variability, isolating the effect of temperature fluctuations from time-invariant country-characteristics (Dell, Jones, & Olken, 2014).

A drawback of the dataset is that it does not include climate anomaly data averaged across the country. Simultaneously, it allows for greater spatial accuracy through its 0.5-degree by 0.5-degree resolution grid. Thus, our analysis will only include temperature anomalies using data from coordinates averaged across the country's capital city. It was chosen as it is assumed that a larger GDP-output percentage, with greater GDP per capita, is expected in capital cities relative to other, more rural cities. However, it is important to note that this may underestimate the influence of temperature deviations on more rural, agriculturally focused regions that may not only have different temperature variations than the capital, especially in larger countries but will also underestimate climate changes influence on economies that are more agriculturally focused, like SSA.

Precipitation data is gathered from the Global Historical Climatology Network dataset (GHCN 2), that uses monthly-total rain-gauge-measured precipitation (P, mm) from station data on a 0.5-degree by 0.5-degree resolution grid between 1900–2017 (Matsuura & Willmott, 2018). The current study adopts similar temporal dimensions for precipitation to that of the temperature anomaly with annual data averages between 1970–2017 for the 84 countries. The data is converted into precipitation anomalies, measured by the deviations in yearly precipitation using 1981–2010 as the historical average. However, precipitation data was available as a country-wide average instead of focusing on capital-specific climate variations, allowing us to better assess the precipitation anomalies impact on the entire country. However, encompassing a broader impact of precipitation deviations on country-wide averages neglects regional heterogeneity that may influence regions differently within each country.

All other variables necessary to measure the impact of climate variations on economic growth are obtained through The World Development Indicators (World Bank, 2020). Data for hereafter mentioned variables are obtained for each country between 1970–2018, configuring a rich, unbalanced panel with a maximum of $T = 48$ and an average of $T = 42$ for the $N=84$ countries.

Economic growth is measured through the log real GDP per capita (U.S. 2010 $PPP). We chose GDP per capita instead of the more predominant literature approach implementing GDP-level or growth (Sachs & Warner 1997; Gallup et al., 1999; Nordhaus 2006), firstly, as we can take advantage of the panel data that can better observe variations over time — providing better econometric estimations than cross-sectional approaches (Hsiao et al., 1995), and also as it safeguards against any confounding population effects over-time, as using GDP-level may underestimate per-capita temperature effects if population increases.

For subsequent robustness tests, we also implement controls to ensure that the model is not influenced by omitted variables that may impact per-capita growth. Population growth is added to account for changes in population influencing per-capita GDP. Human capital investment is proxied by life expectancy, infant mortality, and primary school enrolment rates (Mankiw et al., 1992; Abidoye & Odusola, 2015). Furthermore, technological progress and spillover effects are controlled by foreign direct investments (FDI) and secondary school enrolment (Borensztein et al., 1998; Hübler, 2017).

Descriptive Statistics

Table 1 displays summary statistics for all covariates involved in exploring the impact of climate variations on economic growth in the 84-country sample. At first glance, we can deduce that most of the variables are probably customarily distributed, given that the means are similar to the median observations for most variables. However, Table 1 offers early evidence that some of the control variables, namely primary and secondary school enrolment may be not-normally distributed given large disparities between their median and mean values. Regarding the spread of the data, we can see that particularly for the control variables, most covariates are highly varied, especially infant mortality rates, life expectancy at birth and both primary and secondary school enrolment where standard deviations are all above 10. It is important as there is likely a large disparity amongst these variables between the SSA and OECD samples.

For the 84-country dataset, all variables included some observations between 1970–2018 for every country, apart from precipitation anomalies as the GHCN had no observations for Seychelles, subsequently being omitted from model estimates controlling for precipitation anomalies. Apart from primary and secondary school enrollment rates that average only $T \approx 24$ and $T \approx 16$ years of observations per country, all other variables contain

Table 1
Descriptive Statistics

Variable Name	Definition	Source	Obs.	Mean	Median	Mia.	Max.	Std. Dev.
Main Variables								
LGDC 10	Log GDP per Capita (U.S. 2010 $PPP)	World Bank	3630	3.63	3.66	2.22	5.05	0.77
TempAnom	Temperature deviation from historical norms	GHCN	4116	−0.04	−0.04	−2.25	2.03	0.55
PrecAnom	Precipitation deviation f om historical norms	GHCN	3735	6.25	2.76	−1444.6	1732.1	151.19
Hot	Dummy coded 1 if a country was above the median average temperature of the sample in 2018	World Bank	4116	05	0.5	0	1	0.5
Poor	Dummy coded 1 if a country was below the median GDP per capita ($ 2010) of the sample in 2013	World Bank	4116	05	0.5	0	1	0.5
Control Variables								
POPG	Annual population growth (%)	World Bank	4108	1.75	1.77	−6.77	11.53	1.41
PRIM	Primary school enrollment (net % of population)	World Bank	2054	8133	91.48	10.05	100	2133
SEC	Secondary school enrollment (net % of population)	World Bank	1353	64.77	80.55	0.1	99.91	3138
FDI	Foreign direct investment (net inflows % of GDP)	World Bank	3602	2.95	1.26	−5832	161.82	7.44
LIFE	Life expectancy at birth (years)	World Bank	4106	62.98	62.62	26.17	84.21	12.79
MORT	Infant mortality rates (per l,000 live births)	World Bank	3983	53.57	45.1	1.4	204.4	47.77

T = 47 years of observations per country across the *T = 48* years. Finally, two dummy variables were implemented, coding countries as 1 if the country was either above the median average temperature of the sample (Hot) or if the country was below the median average GDP per capita ($ 2010) of the sample (Poor).

Analysing Table 2 we notice that both temperature and precipitation variables are rich in observations across both regions, with an average *T = 48* years and *T = 45* years of observations respectively per country between 1970–2018. While temperature anomaly data seems normally distributed with identical means and medians (−0.04), precipitation anomalies may be questionable given the mean (6.25) is more than twice the median value (2.76). It is particularly apparent when analysing the data's spread as precipitation has a large standard deviation of 151.17 across the entire sample, with an even greater 178.49 in SSA and a still large 107.7 in OECD countries. It proves that there is variation in precipitation anomalies both between and within regions. This early descriptive analysis is noteworthy as it offers insight into the possible drastic impact precipitation deviations may have on SSA's agriculturally focused sectors (IPCC, 2007).

Interestingly, the mean temperature deviation between 1970–2018 for both SSA and OECD countries are negative at −0.03 and −0.04 degrees lower than the 1981–2010 average, respectively. While surprising at first, it is expected considering the anomaly baseline is taken as an average between 1981–2010 which is likely to be much higher than if 1960–1989 was used as the anomaly reference instead. Thus, one must be tentative when generalising precipitation estimates as it may underestimate the magnitude of temperature increases in both regions. Moreover, we also see that across the sample, the variance in temperature anomalies is greater in OECD than SSA-countries, with greater temperature deviations above (2.03) and below (−2.25) the anomaly average and a larger standard deviation of 0.7 compared to SSA's 0.41.

Table 2
The difference in covariate means for temperature and precipitation anomalies

	Observations	Mean	Median	Minimum	Maximum	Std. Dev.
SSA						
Temperature Anomaly	2303	−0.03	-0.04	−1.37	1.69	0.41
Precipitation Anomaly	1980	11.82	3.52	−1444.63	1732.09	178.49
OECD						
Temperature Anomaly	1813	−0.04	-0.02	−2.25	2.03	0.7
Precipitation Anomaly	1665	−0.68	2.06	−485.05	506.80	107.7
Combined						
Temperature Anomaly	4116	−0.04	−0.04	−2.25	2.03	0.55
Precipitation Anomaly	3735	6.25	2.76	-1444.63	1732.09	151.17

It is interesting to note as the climate literature predominantly focuses on the impact of the temperature changes on growth (Wade & Jennings, 2016) and the vulnerability of developing countries (Dell, Jones, & Olken, 2012), rather than the magnitude of the temperature changes between developed and developing regions.

Although both SSA and OECD countries have seen a consistent increase in temperature across the 48-year period, with anomalies reaching above historical averages in the 21st century, there is a noticeably larger variation and steeper increase in temperature in OECD countries relative to SSA countries.

Analysis of precipitation anomalies is more challenging. As aforementioned, the variation in precipitation anomalies across the entire sample is large, particularly in SSA. Moreover, SSA sports both the largest deviation above (1732.09) and below (−1444.63) the historical precipitation averages compared to the OECD's most extreme precipitation deviations of −485.05 506.8. Further disparities between the samples are noticed when comparing regional precipitation means, with SSA seeing annual mean precipitation of 11.82mm above historical norms. In contrast, OECD countries see average precipitation of 0.68mm below its historical norms.

Unfortunately, Figure 2 offers no tangible trend in precipitation anomalies. Although we can see a considerable variation in precipitation across the years, particularly for SSA, it is difficult to extrapolate a trend regarding whether precipitation increases or decreases over time for either region. However, this preliminary analysis of precipitation anomalies may be interesting, given SSA's larger deviations and its impact on crop-yields in SSA's more agriculturally focused economies (Lobell, Schlenker, & Costa-Roberts, 2011).

Methodology

This paper sets out to elucidate the long-term impact of climate change on economic growth, specifically contrasting the differential impacts climate variations may have between developed (OECD) and developing countries (SSA). Firstly, this section identifies frameworks in previous literature used to model economic growth, while also considering introducing climate variations and their influence on economic growth-models. Finally, it outlines the econometric model adopted, justifying its use relative to past literature downfalls, whilst also considering any possible limitations of the proposed methods.

Growth Model

Following from general growth frameworks delineating how explanatory variables influence economic growth, popularised by Barro (1991)

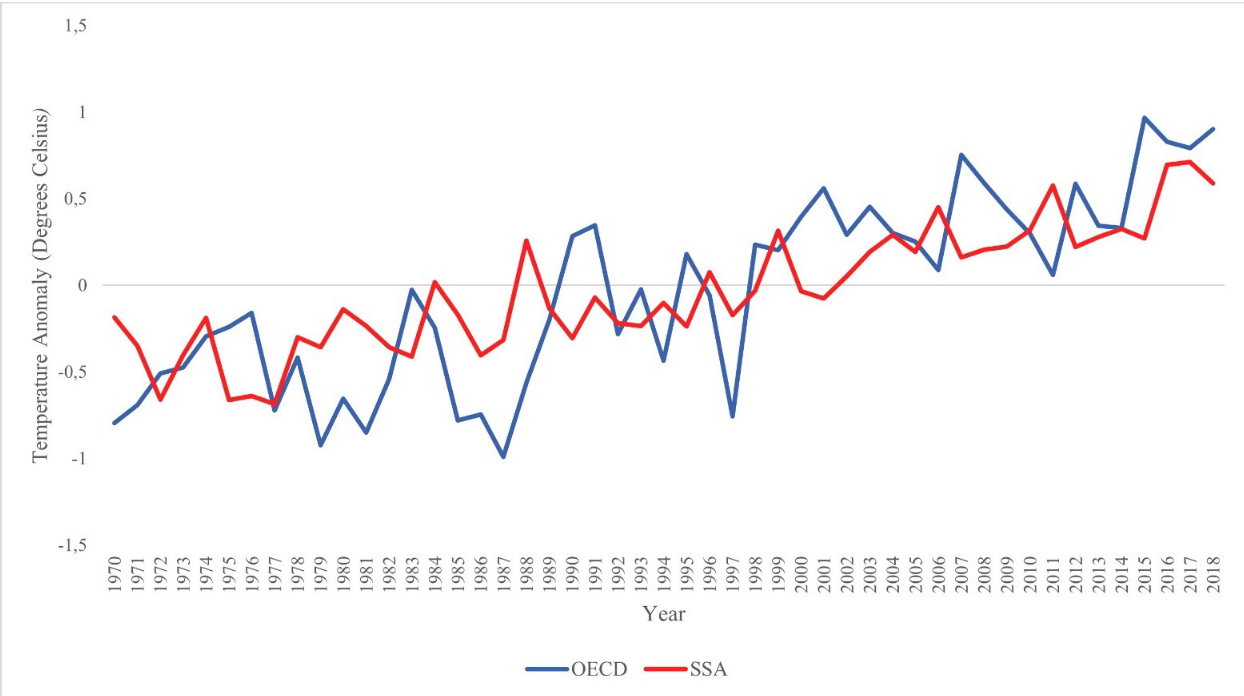

Fig. 1. Average Annual Temperature Deviation from Historical Norms between 1970–2018

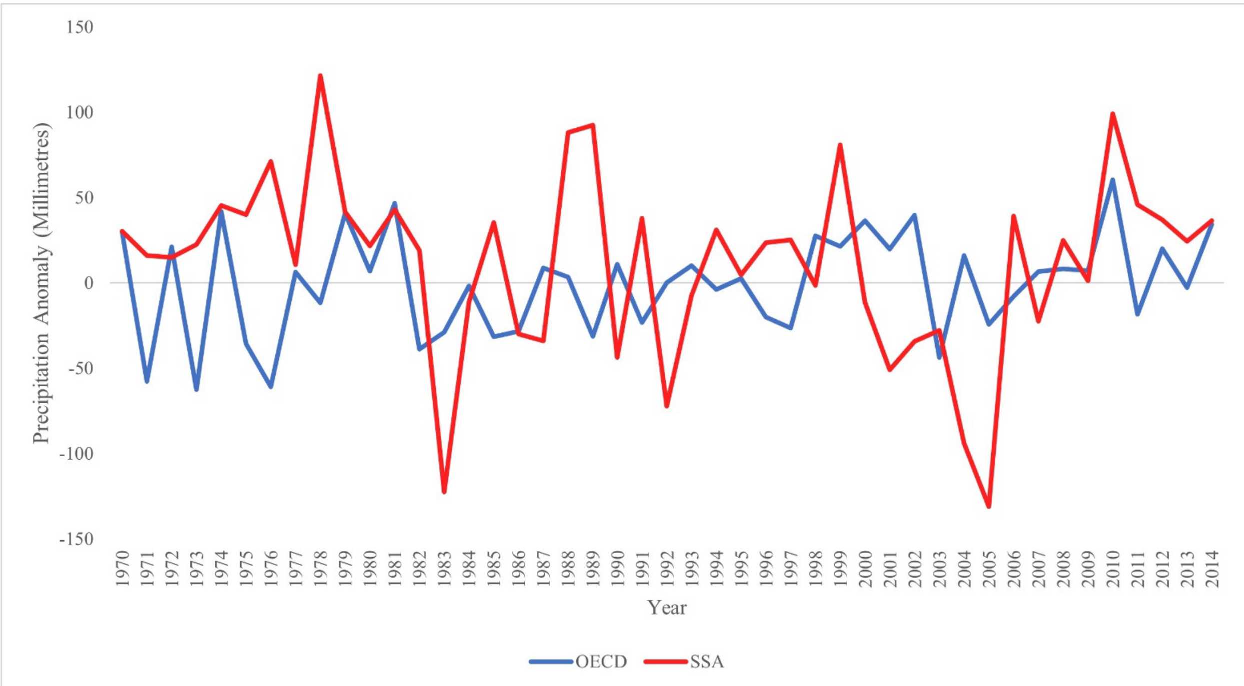

Fig. 2. Average Annual Precipitation Deviation from Historical Norms between 1970–2014

and Sala-i-Martin (1997), and seminal theoretical growth models by Merton (1975), and Binder and Pesaran (1999) developing single economy stochastic growth models, we adopt Kahn et al.'s (2019) approach and expand this literature to a growth process including climate change as an endogenous variable influencing growth in a cross-country model.

I assume that $N = 84$ countries share common technologies but differ in their country-specific climate variations. Consider a set of countries whose aggregate a production function describes production possibilities:

$$Y_{it} = \mathcal{F}\left(\wedge_{it} L_{it}, K_{it}\right),$$

where K_{it} and L_{it} are capital and labour inputs with $\wedge_{it}$ as a scale variable determining labour productivity in an economy for country *i,* at time *t.* I assume that labour productivity, measured by

GDP per capita, is dictated not only by general technological factors but also country-specific climate variables. Climate variables are denoted T_{it} and P_{it} for average temperature and precipitation, respectively. However, I consider that labour productivity is only impacted by climate change when the variables deviate from their historical norms, expressed by $T_{i,t-1}(\eta)$ and $P_{i,t-1}(\eta)$ for temperature and precipitation historical norms where η is the time-scale in the number of years used to calculate historical norms. The assumption is made that technology is neutral over historical norms meaning that technology does not have supplementary effects on labour productivity, given that climate variables do not deviate from historical norms over a given time-horizon. It is intuitive and confirmed in the literature suggesting that hotter countries including Singapore have technologically adapted to harsher climates through air conditioning (Kahn et al., 2019), while opposing effects are found whereby heat-waves are more frequently fatal in colder countries that are less acclimatised to hotter temperatures, reinforcing that different countries adapt to their temperature niche (Heutel et al., 2016).

By accommodating for deviations in climate variables instead of trended temperature variables widespread in the literature (Barrios et al., 2010; Dell, Jones, & Olken, 2012), we can account for any asymmetric effects of climate change on economic growth. Moreover, utilising deviations in climate variables makes it unlikely that the variables have unit roots and counters potential downfalls of linearised climate change trends.

Panel ARDL

The first panel ARDL model will interpret how global temperatures have evolved between 1970–2018 with reference to 1981–2010 historical norms. Allowing for heterogeneous effects between the 84-country sample, country-specific regressions calculating changes in temperature over-time are estimated by:

$$T_{it} = \alpha_i + \beta_{it} + \varepsilon_{it},\ for\, i = 1, 2, \ldots, N = 84,$$

where T_{it} signifies the average temperature of country *i* at time *t*, α_{it} is the country-specific fixed-effect (FE), β_{it} is the individual country's annual average temperature change and ε_{it}, is a serially uncorrelated stochastic shock.

Adopting the above mentioned theoretical growth model, we can estimate the long-term economic impact of climate change on per-capita growth using the panel ARDL model:

$$\Delta y_{it} = \alpha_i + \sum_{\iota=1}^{p} \varphi\iota \Delta y_{i,t-\iota} + \sum_{\iota=1}^{p} \beta'\iota \Delta x_{i,t-\iota}(\eta) + \varepsilon_{it}$$

$$for\, i = 1, 2, \ldots, N = 84, \quad (2)$$

where y_{it} is the log of real GDP per-capita for country *i* in year *t*, α_{it} is the country-specific FE, $x_{i,t}(\eta) = [C_{it} - C_{i,t-1}(\eta)]'$, where $C_{it} = (T_{it}, P_{it})'$ and $C_{i,t-1}(\eta) = [T_{i,t-1}(\eta), P_{i,t-1}(\eta)]'$. Here, T_{it} and P_{it} are temperature and precipitation averages, respectively for country *i* at year *t*, whereas $T_{i,t-1}(\eta)$ and $P_{i,t-1}(\eta)$ are temperature and precipitation η=1981–2010 historical norms. Hence, $x_{i,t}(\eta)$ captures the temperature and precipitation anomalies (denoted in vector C) as they calculate the difference between an observed temperature or precipitation for any country *i* in a given year *y*, relative to their respective historical norm averages.

While I could not choose the historical norm time-horizon as the NOAA dataset already predetermined them, fortunately, climate norms in the literature are typically moving averages of a prior 20–30 year-period, large enough to make annual variations in historical norms small, making 1981–2010 a robust historical norm reference (Arguez et al., 2012; Vose et al., 2014; Abidoye & Odusola, 2015; Kahn et al., 2019).

In this paper, an ARDL specification is used to model both the evolution of global temperatures per-country between 1970–2018 and the long-term impact of climate change on growth. Pesaran and Smith (1995), Pesaran and Shin (1999) and Pesaran et al. (2001) prove that traditional ARDL models can be extrapolated for long-run analysis and are valid irrespective of whether underlying variables are *I* (0) or *I* (1). Moreover, it is a robust approach against omitted variable biases and bi-directional feedback effects between per-capita growth and its long-run determinants — making it an appropriate model for this paper. Furthermore, Pesaran et al. (2001) explicate the advantages of the ARDL model against other estimation methods used in the literature such as dynamic panel models (Hsiao & Anderson, 1981), or the use of instrumental variables (Arellano & Bover, 1995) as these methods often produce inconsistent estimates of parameters if coefficients are heterogeneous across countries (Cerqueira et al., 2018). Furthermore, by utilising a panel that offers more variability than cross-sectional approaches, estimates are less susceptible to collinearity among variables, allowing for more accurate estimates of heterogeneous effects among countries.

For ARDL models to be a robust technique and overcome autocorrelation problems, the model's dynamic specification needs to be augmented with sufficient lags, making the regressors weakly exogenous (Chudik et al., 2017). It is intuitive to believe that the impact of climate change on economic growth will have lasting, lagged effects. However, while previous literature assumes an arbitrary lag of p = 4 years to be sufficient (Kahn et al., 2019), this paper adopts the AIC whose premise is to decide which lags offer new 'information' model. I set the maximum lag-order to 5-years and chose the preferred ARDL model based on the lowest AIC value when re-estimating models for robustness tests. A maximum lag-order of 5 was chosen, not only because it is similar to the previous literature chosen lag-lengths, but also because 5-years is an appropriate amount of time to analyse both the lagged-effects of climate change and also notice any potential lagged retaliatory environmental policy-effects or the influence of policies based on new governmental elects as terms usually last 4-years. Moreover, by employing multiple climate lags, one can elucidate whether the effects of climate variations on economic growth are temporary, persistent or vary over-time as countries adapt differently to climate changes.

However, the panel sample contains $N = 84$ countries for $T = 48$ years, making the cross-sectional dimension larger than the time-dimension. It may be a problem as reporting standard FE estimates for the long-run impacts of climate variations on per-capita growth may be biased from small-T values if any regressors are not strictly exogenous (Chudik et al. 2018). Thus, the lagged dependent variable is included to counter any bias estimates, although one must be circumspect when extrapolating results.

Results

The Evolution of Climate Change

This section explores how global temperatures have evolved between 1970–2018. Equation (1) is employed using a panel ARDL model across $N = 84$ countries to estimate country-specific regressions, allowing for significant heterogeneity between countries concerning temperature anomalies.

Table 3 illustrates how temperatures deviate annually for each of the 84-countries. The entire sample value was estimated by $\beta_t = N^{-1}\sum_{i=1}^{N}\beta_{it}$, with individual countries values estimated by β_{it}. The ARDL estimates demonstrate incontrovertible evidence that between 1970–2018, yearly temperatures have been increasing for all countries relative to 1981–2010 averages. In fact, only 2 countries (2.3 per cent of cases), namely Chile and New Zealand are insignificant, yet still positive with 0.0038 °C and 0.0041 °C increases in their yearly temperatures relative to the historical norms. For the other 82 countries, 7 estimates (8.3 per cent of cases) are significant at the $\alpha = 0.05$ level whereas the other 75 estimates (89.2 per cent of cases) are significant at the $\alpha = 0.01$ level. Estimates vary between Chile's 0.0038 °C and France's 0.0462 °C annual temperature increases. Figure 3's histogram illustrates the frequency of temperature deviations per-country in 0.01 °C intervals. The most common yearly temperature deviations lying between 0.01–0.03 °C increases per-year in which 64 (76.19 per cent of cases) lie.

The average annual temperature increase across the entire sample is 0.023 °C, showing that over the whole 48-year average, countries have increased by roughly 1.104 °C. Unexpectedly, it turns out that annual temperature increases are influenced by larger increases in OECD (0.0326 °C) countries relative to SSA (0.0146 °C) countries. It is surprising given that the literature focuses on temperature deviations adversely impacting growth in developing (SSA) countries more than developed (OECD) countries (Stern, 2006; Dell, Jones, & Olken, 2014). However, while temperatures seem to deviate more in OECD countries, it does not imply that OECD countries are worse affected by these variations.

These estimates are corroborated within the recent literature. Kahn et al.'s (2019) 174-country sample finds that 172 countries (98.9 per cent of the sample) see annual temperature increases, with estimates between −0.0008 °C and 0.019 °C

Table 3
Annual global temperature deviations between 1970–2018

Country	β*it*	Country	β*it*	Country	β*it*
Angola	0.0184***	Gambia	0.0209***	Nigeria	0.0247***
Australia	0.0136***	Germany	0.0255***	Norway	0.019**
Austria	0.0418***	Ghana	0.0266***	Poland	0.0265***
Belgium	0.0222***	Greece	0.0173***	Portgual	0.0316***
Benin	0.0227***	Guinea	0.0211***	Rwanda	0.0141***
Botswana	0.0187***	Guinea-Bissau	0.0209***	Sao Tome and Principe	0.0175***
Burkina Faso	0.0221***	Hungary	0.0418***	Senegal	0.0209***
Burundi	0.0222***	Iceland	0.015***	Seychelles	0.0158***
Cameroon	0.0172***	Ireland	0.0187***	Sierra Leone	0.0211***
Canada	0.0361***	Israel	0.0353***	Slovakia	0.0418***
Cape Verde	0.0191***	Italy	0.0299***	Slovenia	0.0436***
Central African Republic	0.0236***	Japan	0.0194***	Somalia	0.0147***
Chad	0.0259***	Kenya	0.0215***	South Africa	0.0091***
Chile	0.0038	Latvia	0.0167**	South Korea	0.0216***
Colombia	0.0212***	Lesotho	0.0216***	Spain	0.0461***
Comoros	0.0092***	Liberia	0.0211***	Sudan	0.036***
Congo DR	0.0176***	Lithuania	0.0303***	Sweden	0.0163**
Cote d'lvoire	0.0281***	Luxembourg	0.0455***	Switzerland	0.0455***
Czech Republic	0.0255***	Madagascar	0.0158***	Tanzania	0.0216***
Denmark	0.019**	Malawi	0.0208***	Togo	0.0227***
Djibouti	0.0219***	Mali	0.0251***	Turkey	0.0277***
Equatorial Guinea	0.0175***	Mauritania	0.0202***	Uganda	0.0193***
Eritrea	0.0205***	Mauritius	0.0082***	United Kingdom	0.022***
Estonia	0.0167**	Mexico	0.0152***	United States	0.0153**
Eswatini	0.0147***	Mozambique	0.0147***	Zambia	0.0216***
Ethiopia	0.0218***	Namibia	0.0197***	Zimbabwe	0.0182***
Finland	0.0234**	Netherlands	0.0222***	Sample	0.0227***
France	0.0462***	New Zealand	0.0041	OECD	0.0326***
Gabon	0.0175***	Niger	0.0248***	Sub-Sahar an Africa	0.0146***

Note. Significance is highlighted with * for $\alpha < 0.1$, ** for $\alpha < 0.05$ and *** for $\alpha < 0.01$.

across a 1900–2014 time-horizon with greater estimates in temperate climates including Canada and Russia. The entire samples temperature increase of 0.027 ºC is in line with the IPCC's (2013) 0.0175 ºC global annual temperature increase.

Long-term Impacts of Climate Change on Growth

This section estimates the long-term economic impact of climate change variables on the log real GDP per-capita between 1970–2018. Equa-

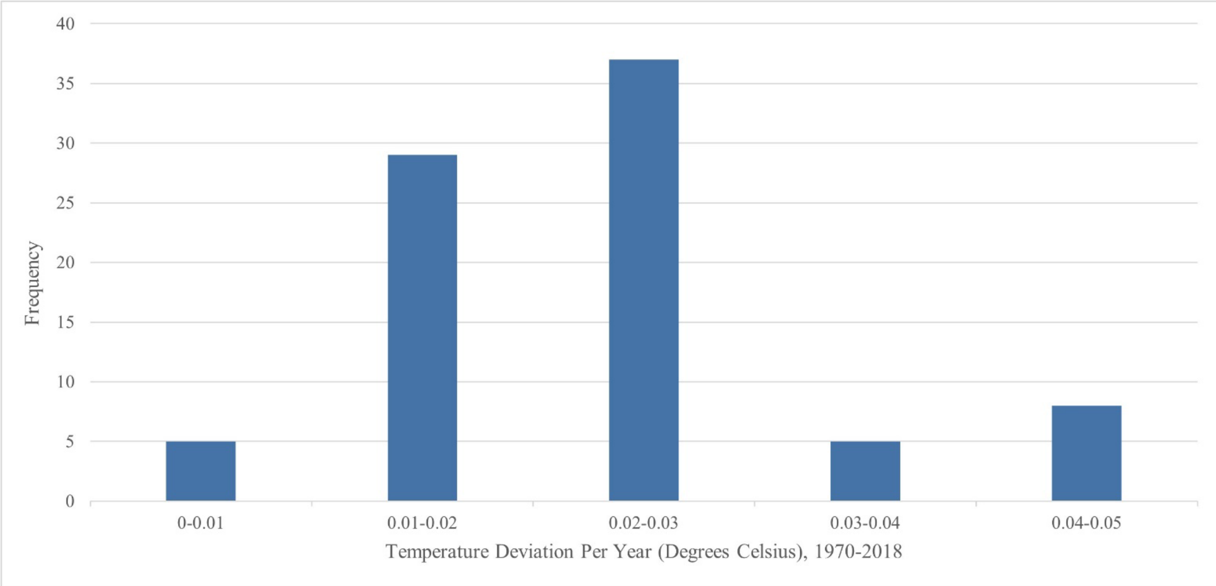

Fig. 3. Histogram depicting temperature deviation frequencies per 0.01-degree interval

tion (2) is employed using a panel ARDL model across $N = 84$ countries, allowing for significant heterogeneous climate effects between countries.

Table 4 provides the summary of 3 panel ARDL regressions including both temperature and precipitation anomaly variables in a baseline model ($ARDL^a$), just temperature anomalies ($ARDL^b$) and just precipitation anomalies ($ARDL^c$), and their influences on the log GDP per-capita. FE estimates are reported, with robust standard errors in brackets. The lagged dependent variables are included to overcome any potential bias with FE models. 'TempAnom' and 'PrecAnom' denote temperature and precipitation anomalies, respectively. As aforementioned, the ARDL lag-orders are chosen based on the AIC, with the lowest values taken as the preferred model.

The baseline model $ARDL^a$ adopts a lag of 1-year for the dependent variable and the precipitation anomaly, with no lags for the temperature anomaly. $ARDL^a$ suggests that neither climate variables significantly impact log GDP per capita. While only slightly insignificant, the temperature anomaly indicates that an increase in temperature as it deviates from historical norms has a marginally positive impact on log GDP per-capita when not lagged. Conversely, while both the lagged and non-lagged precipitation anomaly variables show a negative sign, the coefficients are highly insignificant with estimates recorded beyond 5 significant figures. Finally, the intercept is negative and insignificant with the lagged dependent variable as the only significant variable in the baseline model. Despite this, the overall significance of the $ARDL^a$ is significant at $\alpha = 0.001$ with an F-statistic of 909400.

Since the precipitation anomaly was the most insignificant variable, it was dropped from the model and rerun for $ARDL^b$. In contrast, dropping the precipitation anomaly changes the best AIC order to offer 1-year lags to both the dependent and temperature anomaly variables. $ARDL^b$ provides evidence that long-term economic growth is hindered by temperature variations, suggesting that an annual 0.01 °C increase in temperature above its norm significantly reduces real per-capita GDP by 0.017 per cent after a 1-year lag at the $\alpha = 0.01$ level. $ARDL^b$ also notes that a 0.01 °C annual increase in temperature significantly increases real per-capita GDP by 0.01 per cent in the same year as the temperature deviation at $\alpha = 0.05$ level. However, this non-lagged trend is likely explainable as the temperature deviations have had less time to influence per-capita output for that same-year, especially if temperature deviations were more apparent in later months (i.e., warmer winters). It would mean that temperature anomalies likely influence the following years per capita growth through its impact on agricultural output from lagged temperature effects. Overall, $ARDL^b$ as a model is significant at $\alpha = 0.001$ with an F-statistic of 45650. With the omission of PrecAnom, the intercept is now

Table 4
Long-term impacts of climate change anomalies on economic growth

Covariates	ARDL[a]	ARDL[b]	ARDL[c]
Intercept	−0.0012 (0.0019)	0.05*** (0.01)	−0.0013 (0.0019)
Lag (LGDC 10. 1)	1.002*** (0.001)	0.99*** (0.003)	1.002*** (0.001)
TempAnom	0.001 (0.001)	0.01** (0.004)	–
Lag (Tanom. 1)	–	−0.017*** (0.004)	–
PrecAnom	−0.0000 (0.0000)	–	−0.0000 (0.0000)
Lag (ChangePrecip. 1)	−0.0000 (0.0000)	–	−0.0000 (0.0000)
Observations	3174	3602	3174
F	909400***	45650***	1213000***
R− Squared	0.9991	0.9744	0.9991
Adjusted R−Squared	0.9991	0.9743	0.9991
AIC	−14950.18	−4806.21	−14951.72
AIC Order	1.0.1	1.1	1.1

Notes.
Robust standard errors are in parentheses.
Significance is highlighted with * for $\alpha < 0.1$, ** for $\alpha < 0.05$ and *** for $\alpha < 0.01$.

significant and positive, likely suggesting that $ARDL^b$ is a more econometrically robust model.

To ensure that it was appropriate to remove the precipitation, instead of the temperature anomaly, I rerun the regression instead including 'PrecAnom' and omitting 'TempAnom'. $ARDL^c$ justifies the removal of the precipitation instead of the temperature anomaly given that even without the temperature variable, deviation in precipitation from historical norms remains insignificant in its impact on per-capita GDP growth, regardless of whether the precipitation anomaly is specified with or without a lagged-effect. Additionally, both models that include precipitation anomalies register negative and insignificant intercepts, questioning the model's validity.

Differential Impacts for Poorer and Hotter Countries

So far, we have modelled general climate variables' influence on long-term economic growth. However, we are yet to investigate potential asymmetric impacts of climate change on poorer or hotter economies. Given the literature mentioned above deducing that climate change has uneven, detrimental macroeconomic impacts on poorer and hotter countries (IMF, 2017; Avecedo et al., 2018), I add dummies for 'Poor' and 'Hot' countries and augment the previous models by interacting the dummies with the temperature anomalies. By interacting these dummies with the temperature anomaly variable and including them in supplementary ARDL models, I can more easily determine whether climate change has uneven effects on different regions.

Although $ARDL^b$ was the preferred baseline model, I initially considered whether adding the interaction variables would impact the significance of the precipitation anomaly. Table 5 displays the following ARDL estimations for models, including dummy interaction variables. $ARDL^d$ was estimated, including both climate anomalies and both temperature-dummy interactions. The AIC preferred lagging each variable by 1-year, apart from 'HotTemp', which offered no lagged-effects.

$ARDL^d$ reiterates previous estimations, suggesting that precipitation anomalies offer no significant long-run effects on per-capita GDP growth. Once again, the inclusion of precipitation anomalies makes the models intercept insignificant. Reassuringly, temperature anomalies were robust to the addition of dummy interaction variables, with the lagged 'TempAnom' effect becoming more significant, inferring that an annual 0.01 °C increase in temperature above its norm significantly reduces GDP per-capita by 0.024 per cent after a 1-year lag. However, the non-lagged effect becomes slightly insignificant, sporting a negative sign.

For the interaction terms, $ARDL^d$ suggests that an increase in temperature above the historical norm in hotter countries tends to decrease per-capita growth, although this effect was insignificant. Interestingly, the 'PoorTemp' interaction variable suggests that an annual 0.01 °C increase in temperature above the historical average significantly increases GDP per-capita by 0.01 per cent in the initial year, with a smaller 0.007 per cent increase the following year after the temperature deviation. While this contends against theoretical assumptions and previous literature, the analysis will be saved until a better specified model is chosen.

Given the precipitation anomaly was still largely insignificant, an ARDL model with temperature-dummy interactions was re-estimated, omitting 'PrecAnom'. Following this omission, the AIC now preferred a much richer ARDL model in terms of lagged-effects for each variable. Firstly, $ARDL^e$ offers substantial evidence that temperature deviations from historical norms have significant, negative long-run impacts on income-growth. The model suggests that a 0.01 °C increase in temperature above historical norms, estimates between a 0.011 per cent and 0.022 per cent decrease in per-capita income growth annually up to 4-years after the initial temperature deviation. These ranges are substantiated by the recent literature, although previous estimates are slightly higher between a 0.03 per cent and 0.06 per cent annual decrease in per-capita growth (Abidoye & Odusola, 2015; Kahn et al., 2019). Interestingly, we see that after a lag of 5-years, the effect of a temperature increase becomes slightly positive, increasing per-capita income growth by 0.01 per cent at the $\alpha = 0.05$ level. It suggests that the negative climate influences on growth only last 4-years, which is understandable given that are a long-enough time-period for environmental or governmental policies to take-effect to combat the negative impact of climate change as technologies adapt.

Furthermore, $ARDL^e$ estimates suggest that after a lag of 3-years, an increase in temperature above historical norms in hotter countries seem to have significant, negative, long-term impacts on per-capita growth. Table 5 suggests that an annual 0.01 °C increase in temperature above historical norms for hotter-countries decreases real GDP per-capita by 0.084 per cent after 3-years, 7-times greater than the 3-year lagged impact on the entire samples 0.012 per cent decrease in per-capita incomes. Similar to the entire-sample estimates, although a year earlier, per capita incomes begin to rise again by 0.04 per cent after a 4-year lag. It is interesting as it suggests that hotter countries may adapt quicker than sample averages to climate change's negative influences.

Moreover, $ARDL^e$ estimates elucidate that an increase in temperature above historical norms also has significant, negative impacts on income-growth in poorer countries. For the temperature deviation year, per-capita incomes decrease by 0.041 per cent following a 0.01 °C rise in temperature above historical averages. This more immediate negative temperature effect infers that poorer countries are more susceptible to initial shocks in labour productivity following temperature increases, possibly due to a lack of technologies to combat rises in temperature such as air-conditioning. In antithesis, results suggest that poorer-countries see significant increases in GDP per-capita by 0.043 per cent after 1-year, and 0.11 per cent after 3-year lagged-effects that become insignificant and negative after the fourth year (–0.031 per cent). It is interesting and suggests that 'poorer countries adapt faster than other countries after just 1-year following temperature increases above their historical norms.

Finally, both the intercept and lagged dependent variables are significant, suggesting that the model is better specified. Moreover, the overall model outputs an F-statistic of 8313, significant at the $\alpha = 0.001$ level. Ultimately, I reject the null hypotheses that temperature deviations from historical norms do not have adverse, long-run impacts on growth — particularly in poorer and hotter countries. Finally, an additional model with precipitation interactions between development dummies was also estimated, however, the model was omitted as both precipitation interactions were insignificant and adversely manipulated the $ARDL^e$ results, possibly due to multicollinearity between variables. Thus, we fail to reject the null hypothesis that precipitation deviations impact long-term growth.

Robustness Tests

I have previously shown that the initially preferred $ARDL^b$ model outlining the negative implications of temperature anomalies on per-capita growth is robust to the inclusion of development dummy-interactions with temperature anomalies. In fact, the model was arguably improved to a richer $ARDL^e$ model favouring longer-lags per covariate. However, to further ensure the robustness of $ARDL^e$ The significant impact temperature anomalies have on growth, and I consider two additional robustness controls.

Firstly, it is imperative the variables in $ARDL^e$ maintain their significance when controlling for exogenous variables that may influence real GDP growth per capita. Thus, $ARDL^f$ is estimated with the inclusion of 6-controls, population growth, primary and secondary school enrolment, FDI inflows, life expectancy at birth and infant mortality rates. Reasons for the choice of controls were highlighted above.

AIC prioritises 2-year, and 3-year lags for temperature anomalies and 'HotTemp' interactions while offering no lags for 'PoorTemp' or any control variables. $ARDL^f$ shows that the coefficients signs and significance from $ARDL^e$ They are mostly identical, except a positive and insignificant 'PoorTemp' non-lagged coefficient, and an insignificant second-year lag for temperature anomalies. We see significant, negative impacts of increases in population growth and infant mortality rates on per-capita incomes and significant positive impacts of increases in FDI on income-growth, which are to be expected. However, both school enrolment rates and life expectancy seem to be insignificant.

$ARDL^g$ estimates the same regression but with the omission of life expectancy as it was the most insignificant variable. We see almost

Table 5

ARDL models for the differential impact of climate change on poor and hot countries

Covanates	$ARDL^d$	ARDL–
Intercept	0.001	0.05***
	(0.002)	(0.01)
Lag (LGDC 10. 1)	1.002***	
	(0.001)	(0.003)
Temp A nom	−0.002	0.014**
	(0.001)	(0.005)
Lag (TempAnom. 1)	−0.0024**	−0.022***
	(0.01)	(0.006)
		−0.011*
Lag (TempAnom, 2)	–	(0.006)
		−0.012**
Lag (TempAnom. 3)	–	(0.006)
		−0.017***
Lag (TempAnom 4)	–	(0.006)
Lag (TempAnom 5)		0.01**
	–	
		(0.005)
PrecAnom	−0.0000	
		–
	(0.0000)	
Lag (PrecAnom 1)	−0.0000	
		–
	(0.0000)	
HotTemp	−0.001	0.022
	(0.003)	(0.02)
		−0.01
Lag (HotTemp. 1)	–	(0.02)
		0.002
Lag (HotTemp. 2)	–	(0.02)
Lag (HotTemp. 3)		−0.084***
	–	(0.021)
		0.04**
Lag (HotTemp. 4)	–	
		(0.02)
Poor Temp	0.01***	−0.041**
	(0.003)	(0.02)
Lag (PoorTemp. 1)	0.007***	0.043**
	(0.002)	(0.021)
Lag (PoorTemp. 2)	–	0.034 (0.021)
		0.11***
Lag (PoorTemp. 3)	–	(0.022)
		−0.031
Lag (PoorTemp. 4)	–	(0.02)
Observations	3170	3588
F	462700***	8313***
R−Squared	0.9991	0.9752
Adjusted R−Squared	0.9991	0.9751
AIC	−1500128	−4902.48
AIC Order	1.1.1.0.1	1.5.4.4

Notes.
Robust standard errors are in parentheses.
Significance is highlighted with * for $\alpha < 0.1$, ** for $\alpha < 0.05$ and *** for $\alpha < 0.01$.

Table 6
ARDL robustness tests for controls

Covariates	ARDL[f]	ARDL[g]	ARDL[h]	ARDL[i]
Irtercept	0.033*** (0.012)	0.031*** (0.01)	0.025*** (0.01)	0.12*** (0.02)
Lag (LGDC 10.1)	1.01S*** (0.007)	1.018*** (0.007)	0.99*** (0.001)	0.98*** (0.004)
TempAnom	−0.002 (0.001)	−0.002 (0.001)	−0.001 (0.001)	0.001 (0.004)
Lag (TempAnom. 1)	−0.002* (0.001)	−0.0021* (0.001)	−0.0023** (0.001)	−0.01** (0.004)
Lag (TempAnom. 2)	−0.001 (0.001)	−0.001 (0.001)	−0.001 (0.001)	−0.001 (0.004)
Lag (TempAnom. 3)	–	–	–	−0.001 (0.004)
Lag (TempAnom. 4)	–	–	–	−0.01* (0.003)
HotTemp	0.002 (0.004)	0.002 (0.004)	0.0002 (0.003)	0.004 (0.001)
Lag (HofTemp. 1)	−0.003 (0.003)	−0.003 (0.003)	–	0.01 (0−01)
Lag (HofTemp. 2)	0.001 (0.003)	0.001 (0.003)	–	0.001 (0.01)
Lag (HofTemp. 3)	−0.006** (0.003)	−0.006** (0.003)	–	−0.02* (0.01)
PoorTemp	0.002 (0.003)	0.002 (0.003)	−0.001 (0.003)	−0.07*** (0.01)
Lag (PoorTemp. 1)	–	–	–	0.03** (0.001)
Lag (PoorTemp. 2)	–	–	–	0.04** (0.001)
Lag (PoorTemp. 3)	–	–	–	0.06** (0.001)
POPG	−0.002*** (0.001)	−0.002*** (0.001)	−0.003*** (0.001)	−0.07*** (0.004)
PRIM	0.0000 (0.0000)	0.0000 (0.0000)	0.0000 (0.0000)	–
SEC	0.0000 (0.0000)	0.0000 (0.0000)		
FDI	0.0004*** (0.0001)	0.0004*** (0.0001)	0.0004*** (0.0001)	0.0004** (0.0002)
LIFE	0.0000 (0.0000)		–	–
MORT	−0.002*** (0.001)	−0.002*** (0.001)	−0.005*** (0.000)	−0.007*** (0.000)
Observations	1184	1186	1918	3458
F	142800***	151300***	294900***	13790***
R−Squared	0.9995	0.9995	0.9994	0.9882
Adjuste d R− S quare d	0.9995	0.9995	0.9994	0.9 S 81
AIC	−6473.67	−6476.29	−9S 44.89	−7357.96
AIC Order	1.2.3.0.0.0.0.0.0.0	1.2.3.0.0.0.0.0.0	1.2.0.0.0.0.0.0.	1.4.3.3.0.0.0

Notes.
Robust standard errors are in parentheses.
Significance is highlighted with * for $\alpha < 0.1$, ** for $\alpha < 0.05$ and *** for $\alpha < 0.01$.

identical coefficients and signs with comparison to $ARDL^f$, with continued insignificant relationships between both primary and secondary school enrolment rates and the growth of per-capita incomes. It leads to the removal of secondary school enrolment in $ARDL^h$, and primary school enrolment in $ARDL^i$. The potential reason for the insignificance of the controls is probably that primary and secondary school enrolments only average $T \approx 24$ and $T \approx 16$ years of observations respectively per country, with the lower observation, ranges between 1184–1918 across $ARDL^f$, $ARDL^g$ and $ARDL^h$. With the lack of data for these variables, it may be difficult to extrapolate any meaningful relationships with income-growth over larger time-horizons. Moreover, with sparse coverage in the literature, life-expectancy adds little significance when predicting long-run GDP per-capita growth.

Ultimately, $ARDL^i$ is estimated after omitting the three insignificant controls. Immediately, we notice this AIC specification offers greater potential for analysis given its richer time-lags for all non-control variables. With comparison to $ARDL^e$, the temperature and temperature-dummy interaction variables are lagged 1-less year. Comparing coefficients between $ARDL^e$ and $ARDL^i$, it is noticeable that temperature anomalies remain robust, with 1–4-year lags all maintaining their negative sign, although the second-year and third-year lags become slightly insignificant. As expected, the coefficients are relatively lower when introducing controls suggesting that a 0.01 °C annual increase in temperature above its norm significantly reduces long-run real GDP per-capita by between 0.001 per cent and 0.01 per cent, relative to previously estimated 0.011 per cent and 0.022 per cent income-growth decreases. Despite this, temperature anomalies and their negative long-term impact on growth remain significant and robust when introducing controls.

Regarding the temperature anomaly impacts specific to hotter countries, estimates still indicate that a rise in temperature above historical norms significantly and negatively impacts hotter countries, with a 0.02 per cent fall in annual per-capita GDP after a 3-year lag following a positive 0.01 °C temperature deviation. While the coefficient is slightly smaller than without a control (–0.084), we can deduce that temperature anomaly deviations significantly and negatively impact hotter

Table 7
ARDL robustness tests for alternative temperature anomalies

Covariates	$ARDL^j$	$ARDL^k$
Intercept	0.001 (0.002)	0.05*** (0.01)
Lag (LGDC 10: l)	1.002*** (0.001)	0.99*** (0.003)
TempAnom	−0.0013 (0.001)	0.01** (0.005)
Lag (TempAnom. 1)	−0.002** (0.01)	−0.019*** (0.005)
Lag (TempAnom, 2)	-	−0.011** (0.006)
Lag (TempAnom, 3)	-	−0.01 (0.005)
Lag (TempAnom, 4)	-	−0.015*** (0.005)
PrecAnom	−0.0000 (0.0000)	-
Lag (PrecAnom, 1)	−0.0000 (0.0000)	-
HotTemp	−0.0003 (0.003)	0.026 (0.02)
Lag (HotTemp, 1)	-	−0.01 (0.02)
Lag (HotTemp, 2)	-	−0.004 (0.02)
Lag (HotTemp, 3)	-	−0.06** (0.02)
Lag (HotTemp, 4)	-	0.016 (0.01)
PoorTemp	0.007** (0.003)	−0.045** (0.02)
Lag (PoorTemp, 1)	0.008*** (0.002)	0.03 (0.02)
Lag (PoorTemp, 2)		0.043** (0.02)
Lag (PoorTemp, 3)		0.09*** (0.02)
Observations	3170	3590
F	463200***	9403***
R-Squared	0.9991	0.9752
Adjusted R-Squared	0.9991	0.9751
AIC	−15004.89	−4897.53
AIC Order	1.1.1.0.1	1.4.43

Notes.
Robust standard errors are in parentheses.
Significance is highlighted with * for $\alpha < 0.1$, ** for $\alpha < 0.05$ and *** for $\alpha < 0.01$.

countries — remaining robust to controls. Finally, it is evident that temperature deviations remain robust in their effects on poorer countries, suggesting an immediate 0.07 per cent decrease in per-capita growth when temperatures increase by 0.01 °C above historical norms. Similar to the $ARDL^e$ specification, it seems that poorer countries adapt quicker than others to temperature deviations with positive per-capita growth levels when lagged-effects are considered, with estimates between a significant 0.03–0.06 per cent increase for 1–3-year lags. Moreover, I find that population-growth and infant mortality rates have significant negative, and FDI inflows have significant positive effects on long-term GDP per-capita growth-rates. For all 4 robustness test iterations with controls, models are highly significant with F-statistics ranging between 13790–294900, all significant at the $\alpha = 0.001$ level. Ultimately, apart from slightly diluted impacts on growth when controls are introduced which is expected, the temperature anomalies and their development dummy-interactions remain significantly robust to the introduction of control variables.

Secondly, a critical argument against this paper may be in its use of temperature anomalies in capitals, potentially undervaluing the negative or heterogeneous impact of temperature deviations in more rural, agriculturally focused areas of the country. Therefore, I run a robustness test instead using temperature anomalies averaged across the capital and across 4-extreme coordinates at the most north-south-east and westerly cities to better encapsulate how temperature deviates across the country.

$ARDL^j$ includes the newly averaged temperature anomaly, the new anomalies interactions between both development-dummies, and the reintroduction of the precipitation anomaly. Precipitation was reintroduced to gauge whether estimates change when coupled with a different temperature anomaly estimate. Results from $ARDL^j$ are almost identical with results of the $ARDL^d$. Most importantly, specification suggests that the precipitation anomaly has no significant impact on long-run per-capita growth-rates. Moreover, all coefficient signs and significance levels remain the same across both ARDL specifications, apart from minuscule changes to the coefficients' values by no more than 0.01 decimal places.

Henceforth, our final ARDL model is specified with the omission of precipitation anomalies. Comparable to $ARDL^e$, the exclusion of precipitation anomalies improves the lag-lengths per variable with AIC specifying lags of 4-years for temperature anomalies and 'HotTemp' interactions and lags of 3-years for 'PoorTemp' interactions. Table 7 illustrates that temperature anomalies and their interactions with development-dummies remain robust to more aggregate temperature anomalies measurements. Estimates predict that a 0.01 °C increase in temperature deviations above historical norms have significant, negative, long-term influences on real GDP per capita growth by between 0.01 per cent and 0.019 per cent over a 1–4 year lagged period. These estimates are very similar to the capital adjusted temperature anomalies with decreases ranging between 0.011 per cent and 0.022 per cent. Furthermore, the impacts of temperature deviations on hotter countries remain negative and insignificant across 1-year and 2-year lags and become negative and significant, with a 0.06 per cent annual GDP per-capita decrease after three lagged-years. Thus, proving that temperature increases have more adverse impacts on hotter countries and that these findings are robust against aggregate temperature anomaly estimates. Finally, I also find robust results for poorer economies, with an annual 0.01 °C increase in temperature above historical norms having a significant and immediate negative impact on income-growth of 0.045 per cent for poorer countries. This changes to significant increases in real per-capita growth after a lag of 2-years (0.043 per cent) and 3-years (0.09 per cent). Ultimately, these tests demonstrate that the use of temperature deviations in capital cities offer robust estimates of the aggregate country impacts of temperature changes on long-term real GDP per-capita growth.

Discussion

The present study aims were two-fold; i) identify how country-specific temperatures have varied over the last 48-years relative to their historical averages, and ii) investigate whether deviations in climate variables have a significant impact on economic growth, particularly in hotter, developing countries. Firstly, I documented the evolution of country-specific temperatures between 1970–2018 in a sample of 84 OECD and SSA countries. Secondly, this paper explored the long-term economic impact of climate anomalies on the log real GDP per-capita between 1970–2018 across the same sample. Both research questions implemented a panel ARDL model for their respective quantitative analysis. This paper found that i) temperatures across all countries have consistently increased relative to their historical norms, with 82/84 countries finding significant evidence of annual temperature increases across the 48-year panel. Temperatures were found to increase more dramatically in OECD relative to SSA countries. Secondly, the current paper found ii) robust evidence that deviations of temperatures, particularly increases in temperature relative to historical norms, had significant and negative impacts on long-term per-capita growth. The results also found evidence that temperature deviations disproportionately and negatively affected poorer and hotter countries. However, precipitation variations had no significant effect on long-run income growth.

Long-term Temperature Trends

Relative to 1981–2010 historical norms, the average per-country temperature increase was 0.027 °C annually. Worryingly, temperatures considerably increased for every sample country, with only two countries, namely Chile and New Zealand, being slightly insignificant. Thus, 97.6 per cent of the sample saw significant increases in their relative temperature in the last 48-years, with estimates ranging between Chile's 0.0038 °C to France's 0.0462 °C annual temperature increase. Surprisingly, I found that yearly temperatures increase considerably in OECD (0.0326) countries relative to SSA (0.0146) countries.

My analysis has contributed to the literature in multiple ways. Firstly, it has added to the very sparse literature regarding country-specific temperature increases. Most studies focus on global temperature trends over recent decades rather than country-specific variations (IPCC, 2013; Avecedo et al., 2018). By allowing for country-specific temperature changes, we can better determine climate change heterogeneity between countries. It is useful to economists for multiple reasons as it will enable them to not only analyse which countries have seen specific temperature changes over a given period; allow econometricians to apply this data to determine which countries or regions have been impacted disproportionately in economic-growth models; interpret how different demographics respond to climate change, and finally, allow economists to determine policies to combat regional-specific climate changes from evidence-based policy considerations.

Moreover, by using temperature deviations instead of absolute temperature values, I not only overcome methodology mentioned above issues found when using trended variables, but I also clarify how temperatures have changed over-time relative to historical norms instead of showing the trend of the data. Doing so signifies a potential causal influencer that may be driving temperatures away from historical averages instead of showing that temperature may just be trended in a specific direction. Finally, by analysing updated datasets, I can interpret any potential temperature variations following noticeable rises in GHG emissions in the last decade, ultimately, better informing environmental-policy decisions.

However, it is important to note potential pitfalls of using historical norms as a reference anomaly when calculating increases in average annual temperatures. By utilising temperature variations, my results may have even underestimated the true (absolute) increase in the entire sample's yearly temperatures. It is because I have estimated how temperatures have deviated relative to large 1981–2010 averages. If the data used earlier years as the historical average reference norms or used absolute annual temperature values, results may have shown even further country-specific temperature increases. It is crucial as the literature should not underestimate the impact climate change has on the global economy. Henceforth, my estimates must be extrapolated tentatively, not only as they fail to capture within-country temperature variations that may differ significantly from the country-averages, but also because generalising estimates across longer time-horizons will infer indefinite temperature increases even when policies could be put in place to limit future climate change.

Long-term Impacts of Climate Change on Growth

This paper's central focus was to analyse the long-term impact of climate anomalies on real GDP per-capita between 1970–2018. Results were robust, suggesting that temperature deviations, particularly increase above historical norms, have significant negative impacts on long-term per-capita growth. More worryingly, the fall in per-capita incomes was persistent across 4-lagged years after the initial temperature shock, suggesting that climate change has lasting, long-term impacts on income-growth. Estimates range between a 0.011 per cent and 0.022 per cent annual decline in per-capita incomes following a 0.01 °C temperature increase. These estimates are mostly similar to the literature 0.03 per cent and 0.06 per cent yearly decreases in per-capita growth (Abidoye & Odusola, 2015; Kahn et al., 2019).

There are two additional takeaways from the temperature anomaly estimates; firstly, the non-lagged estimates show a significant positive coefficient on the temperature shock year. This likely suggests that temperature change has less of an effect on labour productivity as opposed to agricultural output considering labour productivity would likely reduce output the year of the temperature shock, whereas agricultural output will be predominantly impacted in lagged years (Seppänen, Fisk, & Faulkner, 2003; Schlenker & Lobell, 2010). Secondly, after the 5-year lag, coefficients became positive. It suggests that the negative influences of temperature variations on income-growth are neutralised 5-years after the shock. It is intuitive given 5-years is a long-enough time-period for environmental policies or governmental changes to take-effect to combat the impact of temperature increases as technologies and policies adapt.

Furthermore, I find that both hotter and poorer economies are significantly and disproportionally impacted by increases in temperatures relative to historical averages. Yet, results differ between the two development-variables. The significant effect for hotter countries is only disproportional after a 3-year lag. The literature can explain it as hotter, agriculturally focused on increasing temperatures over multiple-lags significantly hinder developing countries due to their agricultural dependence (Barrios et al., 2008; Avecedo et al., 2018). Alternatively, poorer-countries see more immediate declines in income-growth — the same year as the temperature shock. It infers that in poor-economies labour productivity may be instantaneously impacted by increases in temperature, which is intuitively based on their lower technological investment than advanced economies adopting more pervasive technologies such as air conditioning (Kahn et al., 2019).

However, estimates contradict some previous literature given that hotter and poorer countries adapt quicker than sample estimates after just 4-year and 1-year lags, respectively. Past papers not only theorise that poorer, hotter countries have a weaker capacity to adapt to climate changes given their lack of resources and weaker institutions (Adger, 2006; Toi, 2008b, Tol, 2009) but also empirically support this suggestion, finding that low-income countries have persistent and lasting negative responses even after 7-lagged years (Dell et al., 2012; Avecedo et al., 2018). Nevertheless, the present results can be explained by Heutel et al. (2016), suggesting that countries with hotter climates better adapt to their temperature niche. It would not only explain why both hotter and poorer countries in the sample have shorter-negative periods of income growth relative to the sample but also corroborates our results that OECD countries have seen greater temperature increases than SSA countries, potentially inferring that even developed economies are struggling to adapt to temperature deviations over-time. An alternative explanation could be that given the increased awareness of climate change and pressures on global-policy to abate GHG emissions, novel policies may be effective at enabling developing countries to better adapt to the difficulties of climate change (IPCC, 2007; Kompas, Pham & Che, 2018).

Nevertheless, this finding is particularly important due to its policy implications. In fact, results suggest that poorer countries react more effectively to temperature deviations than hotter economies. Although interesting given that poorer countries are also typically hotter, findings would infer that policy needs to be particularly focused on the potential temperature-effects on hotter climates as they are more vulnerable to persistent, long-run declines in income-growth following temperature deviations. Moreover, results would also suggest that greater-investment is needed in poorer-countries as they are particularly susceptible to temperature deviations impacting their labour-productivity.

Finally, precipitation anomalies are ubiquitously insignificant in their impact on long-term income growth across all estimations and robustness tests. While inconclusive, this result is substantiated by recent literature all finding no significant impact of precipitation on income-growth (Auffhammer et al., 2011; Avecedo et al., 2018; Kahn et al., 2019). Thus, this paper suggests that temperature variations are more impactful than precipitation variations when understanding climate change's influence on economic growth and development.

This study ultimately adds to the literature through multiple avenues. Firstly, it adopts a robust ARDL model to better study the long-term, heterogeneous impact climate variations have on economic growth between developed (OECD) and developing (SSA) countries. Moreover, by adopting temperature anomalies, I overcome the literature mentioned above difficulties when implementing trended variables. Thirdly, I formulate a robust estimation method based on seminal economic growth-models to substantiate claims made in previous literature that temperature variations negatively impact hotter, developing countries and those precipitation anomalies are inconclusive in their impacts on growth. Finally, I implement the AIC specification method to understand better the differential lagged effects of climate variables in specific regions to better inform policy decision-making.

However, it is also important to mention this paper's limitations that may be useful to consider when expanding future research opportunities. Firstly, while the AIC method was useful in suggesting appropriate lag-intervals to form a more econometrically-robust model, it frequently failed in its task to identify the reactions of specific variables over-multiple lags by regularly understating the number of lags offered to each variable. By doing this, it was difficult to compare how coefficients of lag-lengths change not only when comparing two variables in a model, but also when comparing the same variable between different models as lags often changed between robustness tests. Secondly, to further the model's validity, it would be useful to compare how estimates differ when referencing anomalies using different historical averages because the current results may have underestimated the magnitude of temperature effects on economic growth. Finally, even though using estimates of temperature anomalies at the capital passed robustness tests when comparing to estimates using more aggregate temperature averages across the country, the study still failed to show the true negative extent temperature deviations may have on agriculture assuming that the capital is more services intensive and more rural cities are more agriculturally intensive. Therefore, future studies should either find more inclusive estimates averaged across the entire country or focus on regional temperature variations and their heterogeneous impact on specific areas or countries in SSA to overcome these downfalls.

Policy Implications

The previous results have suggested that temperatures have been rising significantly relative to their historical averages. These temperatures have had significant global impacts, particularly for hotter and developing countries. Next, results must be used as an evidence-base to extract important policy implications. Adaptation to climate change is regarded as a significant future issue, requiring a global effort to contain GHG-emissions consistent with a manageable increase in temperatures to limit any potential long-term impacts of climate change (IMF, 2015; Stern, 2015; Farid et al., 2016). These adaptation-policies are even more significant for developing economies that will face increasing strain on domestic budgets as governments are forced to channel resources away from growth and productivity-enhancing projects, towards countering the costs of damage from extreme temperature variability and reconstruction efforts (Hallegatte, Dumas, & Hourcade, 2010; Wade & Jennings, 2016).

While multiple domestic policies including carbon taxation (Metcalf & Notes, 2008; Covington & Thamotheram, 2015) and investment into sustainable energy (Wade & Jennings, 2016) have been suggested to limit anthropogenic GHG-emissions that significantly influence climate change, more global policies such as international environmental agreements should also be proposed given the disproportionate impact developed-country emissions have had on the developing world (Schelling, 2000). The United Nations Framework Convention on Climate Change established the Paris Agreement (2015) obliging both developed and developing countries to reduce emissions in high-emission industries to reduce emissions. Recent estimates suggest a decline in developed emissions following more stringent mitigation policies (Kim, 2019). Regardless of which policies are adopted, GHG-emissions' abatement must be a worldwide-effort that fosters sustainable development to reduce climate change's detrimental impact on the global economy.

Conclusions

This paper aimed to analyse the variability in global temperatures over the last half-century and estimate the asymmetric impact on developing countries. Utilising innovative ARDL models for an 84-country sample of OECD and SSA countries between 1970–2018, I found that temperatures have unanimously increased for all sample-countries and that variations in temperature above historical norms significantly reduced income-growth across the entire sample. Most importantly, I found that temperature variations disproportionately affected hotter, poorer SSA countries. However, the study also found some original results. Firstly, OECD countries' temperatures have increased more quickly relative to their historical norms than SSA-countries. Secondly, while poorer and developing countries are more adversely affected by temperature variations, they seem to recover more rapidly from temperature shocks than sample averages. Concurring with the literature, I found no evidence that precipitation impacts long-run income-growth.

This study offers multiple additions to the literature. Using ARDL models, this paper better encapsulates both regional and country-specific heterogeneity between effects while also implementing an updated dataset. Moreover, utilising temperature anomalies and AIC specifications overcame previous papers' methodological downfalls. However, caution should be taken when extrapolating results as using temperature anomalies with larger historical norm averages may have significantly underestimated the impact of climate change. Further studies should consider the suitability of AIC, making a comparison between models difficult and inconsistent. Future research could also build on this paper's foundations by potentially looking at the impact of regional-specific climate shocks on SSA, given the dataset's great spatial-dimensions.

This topic is interesting and incredibly important, given its paradoxically disproportionate effect on developing countries and its potentially devastating unmitigated effects on the entire globe. While the analysis emphasised the impact of climate change on SSA, it also highlights that all countries feel the negative effects of unmitigated temperature increases. Going forward, all nations must consider the detrimental impact of climate change when creating policies towards their future development. With a global effort, combatting climate change may be the fundamental driver that fosters worldwide sustainable development.

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Макроэкономические последствия изменения климата для стран Африки к югу от Сахары: аргументы в пользу устойчивого развития

Айдын Сандалли

Аннотация. Несмотря на то, что изменение климата имеет серьезные глобальные последствия, считается, что они непропорционально сильно проявляются в развивающихся регионах с жарким климатом. В данной статье эти утверждения исследуются с использованием панельных данных для 84 стран ОЭСР и стран Африки к югу от Сахары в период с 1970 по 2018 г. В работе анализируется эволюция температур в конкретных странах, а также долгосрочное экономическое влияние колебаний температуры и осадков на ВВП на душу населения. Используя панельную модель авторегрессивного распределенного запаздывания, автор констатирует: поскольку отклонения температуры выше исторических норм произошли одновременно во всех исследуемых странах, то одномоментно и значительно здесь снизился и рост доходов. Никакой существенной связи между выпадением осадков и ростом доходов не обнаружено. При взаимодействии «бедных» и «жарких» стран автор обнаружил, что колебания температуры непропорционально сильно влияют как на более жаркие, так и на более бедные страны Африки к югу от Сахары. Температуры в странах ОЭСР росли быстрее по сравнению с их историческими нормами, чем в странах Африки к югу от Сахары. И хотя более бедные и развивающиеся страны больше страдают от колебаний температуры, они, похоже, быстрее восстанавливаются после температурных шоков, чем страны среднего уровня. Автор объясняет эти результаты и связывает их с потенциальными последствиями для политики в отношении глобального устойчивого развития и борьбы с выбросами парниковых газов.
Ключевые слова: Африка к югу от Сахары; изменение климата; ВВП на душу населения; снижение выбросов парниковых газов; колебания температуры