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RESEARCH ARTICLE

The effect of climate change on economic growth: evidence from Sub-Saharan Africa

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Abstract This study is a contribution to the empirics of climate change and its effect on sustainable economic growth in Sub-Saharan Africa (SSA). Using data on two climate variables: temperature and precipitation, and employing panel cointegration econometric technique of the long- and short-run effects of climate change on growth, we establish that temperatures beyond 24.9 °C would significantly reduce economic performance in SSA. Furthermore, we show that the relationship between real GDP per capita on one hand and temperature on the other is intrinsically nonlinear.

Keywords Climate change · Sub-Saharan Africa · Economic growth · Panel cointegration

JEL Classification C14 · C23 · O11 · O13 · O40 · Q5

1 Introduction

One of the areas of contention in environmental economics is the nexus between continued economic growth and environmental sustainability. The pessimistic view is that continued growth is incompatible with environmental sustainability since the growth process requires the use of the environment both as a source of energy and raw materials and, as a sink for its wastes (solid, gas and liquid) all of which harm

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the environment. According to this school of thought, the sure way to environmental sustainability is to halt growth. However, the optimistic school of thought is of the view that continued economic growth need not be incompatible with environmental sustainability in a world of continuous technological change. This view emphasizes the importance of using green technologies and other alternative ways of production and consumption that do not compromise economic growth both in the medium to long term. Thus, a concerted global effort that takes into account cost-effective instruments of mitigating the effects of rising global temperatures would in the end promote, and not harm economic growth.

The empirical evidence on this debate is of much relevance to growth and environmental policies in the developing world, more so in Sub-Sahara Africa (SSA) where income levels are below acceptable standards. Ensuring sustained long-run growth and environmental sustainability requires prior establishment of the nexus between economic growth and the environment. Recent attention has shifted to the pair-wise nexuses between climate change and economic growth, economic growth and emissions, and emissions and climate change. However, a huge gap remains, particularly, on the empirical nexus between economic growth and climate change. This paper looks at the effect of climate change on sustainable growth for a panel of SSA countries using panel cointegration modelling techniques. We explore and analyse the effects of climate change on economic growth.

Although global warming is a problem that all countries have to contend with, the costs and benefits of rising global temperatures tend to vary across countries and regions. Most studies indicate that poor countries, particularly those in SSA would bear the brunt of climate change (see Lanzafame 2012). The overwhelming reliance on agriculture and other climate-sensitive sectors for production as well as the limited capacity to respond appropriately to climate-related shocks tends to expose the African continent to the vagaries of extreme weather conditions (Stern 2006). See for instance Jiang and Koo (2014), Tanaka et al. (2011) and Kumar and Managi (2014) for more elaborate discussions and evidence on climate change impact on agriculture and the role of adaptation. Thus, by focusing exclusively on SSA, we are able to obviate some of the nuances that are left undetected in the global debate, and contribute to the search for appropriate policy responses at the national and international levels.

In this paper, we estimate the effect of climate change on long-run economic growth for a selected sample of SSA countries using panel cointegration. Our estimation results reveal an unanticipated long-run relationship between temperature and economic growth. This is true about precipitation in the long run. However, in the short run, we establish that temperature has a more pernicious effect on economic growth. Specifically, a percentage increase in temperature significantly reduces economic performance in SSA by approximately 0.13 %, ceteris paribus. Furthermore, we show that the relationship between real GDP per capita on one hand and the climate variables on the other hand is intrinsically nonlinear.

The rest of the paper is organized as follows. In Sect. 2, we survey the literature, examining particularly the effect of climate on growth. We establish several empirical relationships between climate and economic production and other indicators of environmental quality and sustainable growth. Section 3 provides the information on data sources, model specification and estimation strategy. Section 4 of the paper presents the results of the panel cointegration analysis. Section 5 concludes.

2 Literature review

There is a considerable debate about what is the sensible policy response to the environmental problems as a consequence of the continued buildup of greenhouse gases. Incidentally, the nascent literature has considerably expounded on the relationship between environmental sustainability and economic growth. In this section, we give an update review of the economics of the problem and appraise the appropriate literature both empirically and theoretically concerning the relationship between climate change and economic growth.

The natural environment plays a dual role in the economic performance of any country: it provides natural resources which function as inputs (both direct and indirect) to the production of goods and services. Man's entire existence, from basic food, air, water, temperature, plants, soil, animals among others are all derived from the environment. From the most basic stone age existence to the most sophisticated modern life of computers and airplanes, the environment has shaped and conditioned man's experience through time and space. At the same time, the environment serves as a dust bin for all waste generated from man's activities. It can thus be said without question that the environment is man, and man is the environment. Without any external disturbance, there exists a delicate balance in the environment where each organism contributes beneficially to the whole. However, the quest for growth and unbridled consumerism has over the years upset the ecological balance. It is to this disequilibrium that many climate scientists and economists have spent a great amount of time and energy analysing with the view to restoring balance once again.

Fankhauser and Tol (2005) identified the channels of transmission from climate change to economic growth. Using a standard neoclassical growth theory as the basic framework of investigation, they identified capital accumulation and savings as the key dynamic channels through which climate change may impact on long-run growth. Since saving and hence investment is the present value of future consumption, climate impact on future consumption and households' welfare is implied. Another potential channel of transmission is the rate of human capital accumulation. Temperature increases slow down the rate of learning and also impact on health of the labour force adversely. The cumulative effect of these is to reduce labour productivity and long-run economic growth.

Milliner and Dietz (2011) have also examined the potential theoretical channels through which climate change may affect long-run economic growth. They maintain that the dichotomy between adaptation and growth on one hand, and mitigation and development on the other is clearly ambiguous. An important conclusion from Milliner and Dietz (2011) is that the task of apportioning investment between productive capital and adaptation investments is a subtle one. Implicit in this finding then is that as an economy develops over time, it will automatically insulate itself from the perils of climate change. For instance, the structural changes that go with economic development will mean less dependent on the more sensitive sectors to climate change such as agriculture.

Following the seminal contributions by Nordhaus (2006) and Dell et al. (2008, 2009), empirical studies that aim to estimate the growth effect of climate change are becoming very popular among empirical macroeconomists. Nordhaus (2006) established key empirical findings of the effect of geographic factors on economic performance (economic growth). Nordhaus (2006) investigated three applications of the G-Econ data base[1] and reported some interesting findings. First, climate-output reversal was detected in the data. Nordhaus (2006) found a negative relationship between temperature (a proxy for climate change) and output per capita but a strongly positive relationship between temperature and output per area (country size adjusted GDP). Another interesting finding reported by Nordhaus is that geographic factors account for much of the income differences between Africa and the rest of the world. The G-Econ data base provided a better estimate of the economic impact of greenhouse warming than has been reported in previous studies.

Dell et al. (2008) used annual data on the variations in temperature and precipitation over a period of 50 years at the global level to examine the effect of climate change on economic activity. Their study reported three primary findings. First, rising temperature significantly reduces economic growth in poor countries, but such effect is insignificant in developed countries. Second, higher temperatures appear to decrease growth rates in poor countries than just the level of output. Third, increases in temperature have wide-ranging effects on poor countries, reducing agricultural output, industrial output and aggregate investment and political instability. These findings reported by Dell et al. (2008) suggest that the effect of climate change at the aggregate level depends on a country's level of development, with the negative effect damped as the country moves up on the development ladder. This implication is consistent with the implications of the theoretical conclusion by Milliner and Dietz (2011) that economic development will automatically insulate countries from the perils of climate change and thus a separate adaptation investment from productive capital accumulation may not make much difference. With regard to precipitation, Dell et al. (2008) concluded that precipitation does not have any significant effect on economic growth. This conclusion is independent of a country's level of development.

In a related study, Dell et al. (2009) combined theory with empirics to further examine the temperature income relationship. Employing data from 12 countries in the Americas, Dell et al. (2009) establish negative cross-sectional inter and intra country relationship between temperature and income. However, as the authors argue, about half of the negative short-run effects of temperature on growth are mitigated through long-run adaptation.

[1] The G-Econ data base measures economic activity for large countries, measured at a 1° latitude and 1° longitude scale.

Abidoye and Odusola (2015) empirically examined the impact of climate change on economic growth in Africa. Using annual data for 34 countries spanning the period 1961–2009, they found a negative impact of climate change on economic growth in Africa. Their study revealed that a 1 °C rise in temperature reduces economic growth by approximately 0.27 percentage points for the region. Considering a sub-sample in the time dimension over the period 1961–2000, they reported a greater negative effect of climate change on growth. Growth falls by 0.41 percentage points per degree celsius rise in temperature in Africa. The implication of this is that over time, the climate impact on growth is damped due to adaptation measures. This contradicts the popular view that the economic impact of climate change becomes worse as time elapses. However, we should not be too happy about this finding since Abidoye and Odusola (2015) did not control for the possible nonlinearities between climate change and economic growth. This omission can have overwhelming implications for the precision of the estimates reported.

Jones and Olken (2010) analyse the trade effects and export performance of developing countries to climate change and conclude that warmer temperatures tend to dampen export performance of developing countries, predominantly for agriculture and light manufacturing.

Lanzafame (2012) investigated the effects of temperature and rainfall on economic growth in Africa using annual data from 1962 to 2000 for 36 African countries. Using autoregressive distributed lag model for panel data, he finds evidence of both short- and long-run relationship between temperature and per capita income growth. However, the impact of rainfall on growth has little support from the data. The important lesson of Lanzafame (2012) is that African countries have not adapted well to weather shocks, and without proper intervention mechanisms to arrest the alarming effect of climate change growth may be hampered.

From the forgoing discussion, it goes without saying that the deleterious effects of climate change on growth are well established in the literature, particularly for Sub-Saharan African economies: warmer temperatures and falling precipitation reduce the capacity to utilize irrigation to grow crops, and to support export-based agriculture and light industry. This has a feedback loop on growth and poverty reduction efforts. However, the debate so far seems to be one sided. There have been alternative explanations pointing to the need for caution in interpreting evidence presented from the climate data.

Mendelsohn (2009) posits that the effects of climate change may have been overrated in both the theoretical and empirical literature, and probably in the next half century or so presents less threat on a global scale than is currently projected. According to Mendelsohn (2009) extrapolating into 2100, the annual net market impacts of warmer temperatures are a mere 0.1 and 0.5 % of GDP: estimates far too less to have any significant impact in the most immediate period. It thus stands to argue that unbridled intervention could in fact be more detrimental than the perceived threat posed by climate change.

3 Data and empirical strategy

3.1 Data

This empirical paper relies on panel dataset collected from different data sources from 1970 to 2009 for 18 SSA countries.[2] The criterion used in the selection of the candidate countries was based on the availability of data, particularly on the proxies used for climate change. Furthermore, data on real GDP per capita and other macroeconomic variables are gleaned from World Development Indicators and African Development Indicators databases of the World Bank. The Climate data on temperature and precipitation at the country level were taken from the Climate database of the Food and Agricultural Organisation of the United Nations.

The statistics indicate that the mean real GDP per capita for the sampled countries over the period is US$533.6. This reiterates the low income levels of many countries within the region. Though, per capita real GDP can be influenced by the population size of a country, on average, the income levels of most Sub-Saharan African countries are low. The standard deviation of real GDP per capita further confirms that there is not much variability in the income levels of these countries. On the climate side, temperature averaged 24.9 °C within the period across the sample. Also within the period, the minimum and maximum temperatures recorded were 11.8 and 31.6 °C, respectively. Indeed, the temperature values portray that a significant number of the countries included in the sample are found in the tropics. The precipitation values recorded corroborate the tropical nature of the sample units as the mean precipitation recorded was 475.92 millimetres over time and space. However, this variable indicates a significant variation in the sample as the maximum precipitation recorded was 4433 millimetres with the lowest being 1 millimetre annually.

We also present scatter plots of real GDP per capita and the climate variables as a precursor to preview the nature of the relationship between the two variables. The upper panel of Fig. 1 plots the real GDP per capita against the climate variables, while the lower panel plots the logarithms of these variables to reduce the effect of outlying observations in the sample.[3] The plots show that temperature has a negative association with real GDP per capita but the relationship is somewhat weak at lower temperatures. Thus, temperature is detrimental to growth in GDP per capita beyond some threshold. A similar conclusion can be drawn after taking the logarithms of the variables.

Contrarily, precipitation appears to be positively related to income levels as indicated in Fig. 1. Higher precipitation, on average, increases per capita income, since rainfall is deemed to be extremely important to agriculture. In other words, shortfalls in crop production are potentially as a consequence of droughts caused by

[2] Benin, Burkina Faso, Cote d'Ivoire, Ghana, Senegal, Togo, Mali, Niger, South Africa, Congo DR, Zambia, Sudan, Zimbabwe, Madagascar, Mauritania, Cameroun, Kenya and Lesotho.

[3] We also present the plots excluding South Africa from the sample (see Fig. 3 in the Sect. 6). Excluding South Africa from the sample did not alter the direction of association between real income and climate variables.

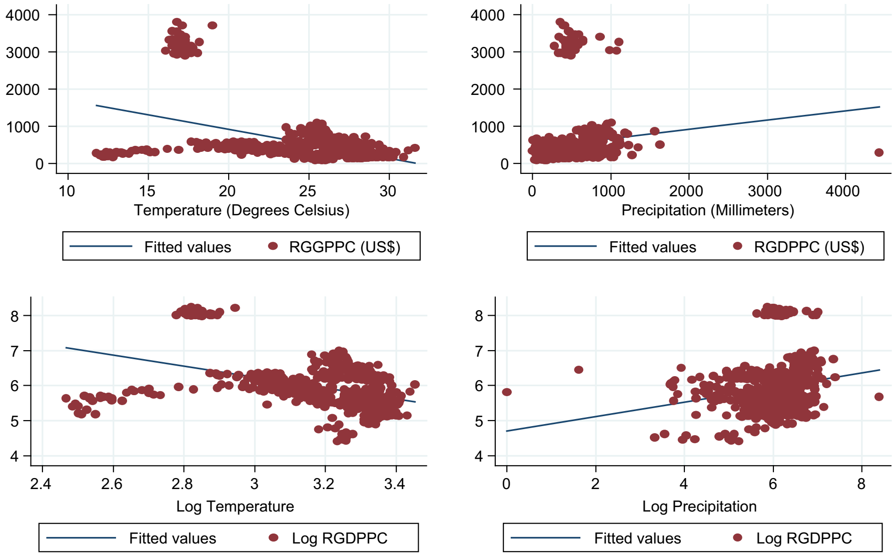

Fig. 1 Scatter plot of real income and climate change variables

low precipitation. However, much of the concentration is found below precipitation values below 1000 millimetres (Fig. 2).

To be sure if there is some uniqueness or heterogeneity in income and climate in the countries, we present the plot of within country variations on these variables.[4] The plot indicates that climatic conditions as well as real GDP per capita vary across the countries. Between-year variations in these variables are also present in the data (see Sect. 6).

3.2 Empirical model

The empirical model of this paper is developed from an augmented neoclassical stochastic aggregate production function with Cobb–Douglas structure. We write this in intensity form as:

$$y_{it} = A_{it} k_{it}^{\alpha} T_{it}^{\tau} P_{it}^{\gamma} e^{\varepsilon_{it}}, \tag{1}$$

where y_{it} is real per capita income for a given country; k_{it} is capital per worker in country; T_{it} is the mean annual temperature; P_{it} is the annual rate of precipitation; ε_{it} is a random error factor and i and t represent country and time. Since both temperature and precipitation are global public goods (bad), they enter the above production function in aggregates rather than per worker terms. A_{it} indicates the state of technology in country i at date t. Following the literature on the modern growth theory, we assume that the level of technology at any point in time depends on foreign aid inflows (ODAY), financial development (DCPY) and openness to

[4] We present the between years variations on these variables in Fig. 4 in the Sect. 6.

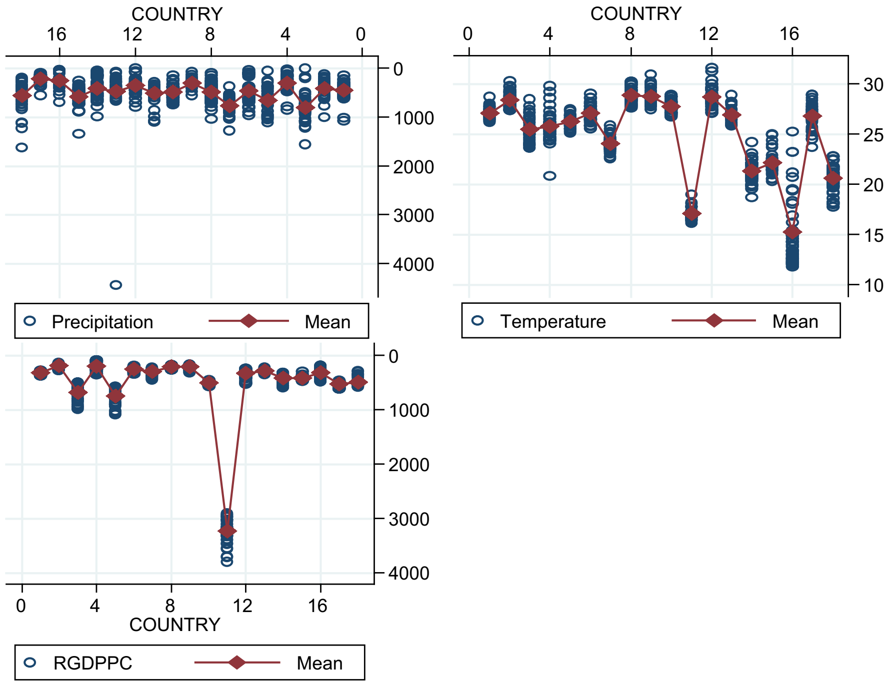

Fig. 2 Heterogeneity in real GDP per capita and climate variables

international trade (TRADEY), among other factors. For brevity, we assume that the state of technology function also has a Cobb–Douglas structure as follows:

$$A_{it} = B(\text{ODAY})_{it}^{\eta}(\text{DCPY})_{it}^{\kappa}(\text{TRADEY})_{it}^{\psi} \tag{2}$$

Substituting Eqs. (2) into (1) and taking logs yields the following empirically estimable model:

$$\begin{aligned} \ln y_{it} = \varphi_{it} + \alpha \ln k_{it} + \tau_{it} \ln T_{it} + \gamma_{it} \ln P_{it} + \eta_{it} \ln(\text{ODAY})_{it} \\ + \theta_{it} \ln(\text{DCPY})_{it} + \psi_{it} \ln(\text{TRADEY})_{it} + \varepsilon_{it} \end{aligned} \tag{3}$$

Estimating Eq. (3) using cross-country panel data is not without challenge. This has not gone unnoticed in the current literature on cross-country growth regressions (see for instance Levine and Renelt 1992; Temple 2000; Rodrik 2012). Rodrik (2012) in particular highlights on parameter heterogeneity, outliers, omitted variables, model uncertainty, measurement error and endogeneity as key challenges to cross-country regressions. In choosing an approach and estimator for this paper, these problems are taken into account.

3.3 Empirical methodology: panel cointegration tests and estimation

The present paper uses the newly developed panel cointegration techniques to evaluate how climate change has impacted on the economic performance of Sub-Saharan African countries. Traditional panel data econometrics rests on micro panels that unremarkably include thousands or hundreds of units (large N), which are tracked over a few study rounds (small T). This study, however, uses macroeconomic variables that are collected for several SSA countries over a significant number of years. Using panel datasets with large N and large T thus presents new challenges to researchers. Since macroeconomic variables are often characterized by nonstationarity, panels with a significant time dimension are subject to spurious relationships. According to Baltagi (2008), the accumulation of observations through time generated two strands of ideas: (1) the use of heterogeneous regressions (one for each country) instead of accepting coefficient homogeneity (implicit in pooled regressions), e.g. Pesaran et al. (1999); and (2) the extension of time series methods (estimators and tests) to panels to deal with nonstationarity and cointegration, e.g. Pedroni (1999).[5]

The use of unit root and cointegration test in panel data analysis has enormous advantages as compared to the already established time series approach. The first advantage is that, finite sample power of the test is tremendously improved by pooling cross sections and time series. In contrast, the conventional unit root tests (e.g. ADF and PP) have been found to have lower power, in particular when the sample size is small. A number of researchers including Levin et al. (2002) and Im et al. (2003) show that, there is a considerable improvement in the power of unit root tests when using panel data other than the univariate testing procedures. Moreover, the use of panel data may be instrumental in offering relevant information regarding the economic systems for the groups of countries considered, rather than singly analysing for each country.

Cointegration analysis in a panel data setting is analogous to the steps usually employed in time series analysis: (1) unit root testing; (2) cointegration testing; and (3) estimation of the long-run and short-run relationships.

3.4 Estimation of the long-run relationship

If there exists cointegration of nonstationary variables, then it becomes relatively peculiar to estimate efficiently the long-run economic relationships between them. Thus, a number of panel estimators have been suggested in the literature. An important difference is that the panel OLS estimator of the (long-run) static regression model, contrary to its time series counterpart, is inconsistent (Baltagi 2008).

Pesaran et al. (1999) suggest a (maximum-likelihood) pooled mean group (PMG) estimator for dynamic heterogeneous panels. The procedure fits an autoregressive

[5] Moreover, the estimators for panel cointegrated models and related statistical tests are often found to have different asymptotic properties from their time series counterparts (Baltagi 2008: 298). An important contribution is Phillips and Moon (1999, 2000), who analyse the limiting distribution of double indexed integrated processes.

distributed lag (ARDL) model to the data, which can be re-specified as an error correction equation to facilitate economic interpretation. Consider the following error correction representation of an ARDL (p, q, q,…, q) model:

$$\Delta y_{it} = \phi_i y_{i,t-1} + \beta_i' X_{it} + \sum_{j=1}^{p-1} \lambda_{ij} \Delta y_{i,t-j} + \sum_{j=0}^{q-1} \delta_{ij}' \Delta X_{i,t-j} + \mu_i + \varepsilon_{it} \quad (4)$$

where X is a vector of explanatory variables, β_i contains information about the long-run impacts, ϕ_i is the error correction term (due to normalization), and δ_{ij} incorporates short-run information. The PMG can be seen as an intermediate procedure, somewhere between the mean group (MG) estimator and the dynamic fixed-effects (DFE) approach. The MG estimator is obtained by estimating N independent regressions and then averaging the (unweighted) coefficients, whilst the DFE requires pooling the data and assuming that the slope coefficients and error variances are the same. The PMG, however, constrains the long-run coefficients to be identical ($\beta_i = \beta_i$ for all i), but allows for variations in the short-run coefficients and error variances across countries (Pesaran et al. 1999). This approach can be used whether the regressors are I(0) or I(1) (Pesaran et al. 1999).

4 Results and discussion

This section presents the results and discussion of the estimated relationship between climate change and economic growth in SSA. Since we are dealing primarily with macroeconomic variables that span over a relatively long period, and hence often found to be nonstationary, we first conduct panel unit root tests to evaluate their order of integration. Next, we apply the panel cointegration tests to ascertain whether there are long-run relationships amongst the variables. In the final step, we estimate the long-run and short-run relationships using the relevant and efficient techniques.

4.1 Panel unit root test results

As pointed out already in the preceding section, several authors have proposed unit root tests based on different assumptions. This study, however, settles on five distinct panel unit root tests on the variables for the period covering 1970–2009: Levin–Lin-Chu's (LLC) t*, Breitung's t, Hadri's Z, Im-Pesaran-Shin's W, and Maddala and Wu's χ^2 statistics. Among these tests, LLC, Breitung and Hadri's tests are based on the common unit root process assumption that the autocorrelation coefficients of the tested variables across cross sections are identical. However, the IPS and ADF-Fisher χ^2 tests rely on the individual unit root process assumption that the autocorrelation coefficients vary across cross sections. In all the test specifications, we include deterministic time trend. In the LLC, IPS and ADF-Fisher tests, cross-sectional means are subtracted to minimize problems arising from cross-sectional dependence. However, Hadri and Breitung tests used in this study allow for cross-sectional dependence. The Schwarz–Bayesian information criterion

(BIC) is used to determine the country-specific lag length for the ADF regressions, with a maximum lag of 3 regarding the LLC and the IPS tests. Further, the Bartlett kernel was used to estimate the long-run variance in the LLC test, with the maximum lags determined by the Newey–West bandwidth selection algorithm. The test results are presented in Table 3 (See Sect. 6).

The test results in general show evidence of nonstationarity in all the variables used in the model in their levels. The LLC test provides strong evidence of nonstationarity in all the variables. Regarding the IPS and ADF-Fisher tests, all the variables were nonstationary with the exception of precipitation and official development assistance. The Breitung test indicates that with the exception of gross capital formation and trade openness, the remaining variables are nonstationary at their levels. Using an alternative test (Hadri test) which has a different null hypothesis of stationarity provides strong evidence that all the variables contain unit roots. It must, however, be emphasized that, although the cross-sectional averages were subtracted from each series (demeaning) prior to applying the LLC, IPS and ADF-Fisher tests, the original versions of Hadri and Breitung tests were also applied, which are not robust to cross dependence and similar conclusions were drawn. Taking the first difference of all the variables yielded stationarity which implies that the series are integrated of order one [i.e. I(1) process].

4.2 Panel cointegration results

A cointegration test is required to avoid the spurious regression problem. A valid inference can be made if a stable equilibrium exists amongst the variables under consideration, albeit we have found that the variables are nonstationary. A case in point, when a linear combination of these nonstationary variables produces stationary error terms. Table 4 presents three variants of panel cointegration in this study. The Pedroni (1999) and Kao (1999) tests use the Schwartz–Bayesian information criterion (SIC) to automatically select the appropriate lag length. Further, spectral estimation is undertaken by the Bartlett kernel with the bandwidth selected by the Newey–West algorithm. While the Pedroni and Kao tests are based on residuals of the long-run static regression, the Fisher cointegration test is based on the multivariate framework of Johansen (1988). Deterministic time trends are included in all specifications. All tests are derived under the null hypothesis of no cointegration. The results of the cointegration tests are provided in Table 4 (See Sect. 6).

The Pedroni's test statistics when we assume common autoregressive coefficients do not provide any support for the presence of cointegration. However, when the between-dimensions (individual autoregressive coefficients) are considered, there appears to be some evidence of cointegration among the variables. This result is further reiterated by Kao's test which rejects the null hypothesis of no cointegration at 5 % level of significance. The Fisher's test based on multivariate framework provides strong evidence of cointegration.

Table 1 Summary statistics of the variables

Variable	Obs	Mean	Std. Dev.	Min	Max
RGDPPC	720	533.55	679.68	82.7	3796
TEMP	720	24.88	4.13	11.8	31.6
PREC	720	475.92	287.25	1	4433
GCFY	720	19.07	9.32	1.6	76.7
TRADEY	720	61.77	30.36	6.3	187.7
DCPY	720	20.95	22.10	0.7	162
ODAY	720	9.30	7.97	0	95.5

4.3 Estimation and interpretation of the long-run and short-run relationships

To estimate the long- and short-run relationship between climate change and economic growth in SSA, having achieved cointegration amongst the variables under consideration, we apply the pooled mean group (PMG) estimator which uses the panel extension of the single equation autoregressive distributed lag (ARDL) model. One advantage of using this strategy is that the error correction representation in the ARDL provides information about the contemporaneous impacts and the speed of adjustment towards equilibrium following a shock. Furthermore, while the long-run coefficients are assumed to be homogeneous (that is, identical across panels), the short-run coefficients are allowed to be heterogeneous (that is, country-specific). Alternatively, we use the mean group (MG) estimator which essentially allows the long-run parameters to change. The poolability assumption of the PMG estimator is thus tested using the Hausman test (Table 1).

The long- and short-run estimates based on PMG and MG estimation strategies are reported in each column of the Table 2. The table presents two alternative models. In model 1, we present the results of the climate variables without accounting for the possible nonlinearities. However, in model 2, we include a quadratic term of temperature and precipitation to account for the possibility of nonlinearities and the consequent threshold effects of climate change on economic performance.

The magnitudes of the long-run coefficients of temperature and precipitation variables (in model 1) represent elasticities of output with respect to each of these variables whereas the magnitudes of the other coefficients are semi-elasticities.[6] Contrarily, in model 2, these long-run coefficients are semi-elasticities.[7] The results of the two estimators generally show consistency in terms of the signs but not statistical significance. However, the error correction terms are as expected,

[6] Data on trade, gross fixed capital formation, domestic credit to private sector and official development assistance are all shares of GDP. We deem it seemingly innocuous not to take the logarithms of these variables in the estimation. Moreover, since our focus is primarily on the climate change variables, interpreting their coefficients in elasticities seems more appropriate.

[7] Including the logarithmic quadratic terms of temperature and precipitation could potentially cause collinearity problems in the estimation. Thus, we do not take the logarithms of these climatic variables.

Table 2 Long and short-run estimation results

	Model 1		Model 2	
	PMG	MG	PMG	MG
Convergence coefficients	−0.057*** (0.013)	−0.2313*** (0.0441)	−0.051*** (0.013)	−0.2311*** (0.0487)
Long-run coefficients				
TEMP	0.0971 (0.5422)	2.1354 (3.5023)	0.5330** (0.2301)	4.1716 (11.1377)
PREC	−0.0505 (0.0347)	−1.4048 (1.2885)	−0.0007** (0.0003)	−0.0027 (0.0040)
$TEMP^2$			−0.0107** (0.0047)	−0.0893 (0.2131)
$PREC^2$			3.19e−07 (2.20e−07)	
GCFY	0.0464*** (0.0066)	−0.0401 (0.0590)	0.0548*** (0.0082)	−0.1593 (0.1510)
TRADEY	0.0046** (0.0023)	0.0382 (0.0254)	0.0038 (0.0024)	0.0374 (0.0561)
DCPY	−0.0106** (0.0043)	0.0206 (0.0286)	−0.0126*** (0.0047)	0.0581* (0.0344)
ODAY	−0.0041 (0.0055)	−0.0082 (0.0249)	−0.0037 (0.0063)	0.0025 (0.0338)
Short-run coefficients				
ΔTEMP	−0.1279*** (0.0414)	−0.0740 (0.0864)	−0.1466 (0.1031)	0.1882 (0.2012)
ΔPREC	0.0037 (0.0040)	0.0044 (0.0054)	0.00004 (0.00005)	0.00002 (0.00001)
$\Delta TEMP^2$			0.0030* (0.0019)	−0.0032 (0.0037)
$\Delta PREC^2$			−2.48e−08 (5.49e−08)	
ΔGCFY	0.0017** (0.0007)	0.0007 (0.0007)	0.0014** (0.0007)	0.0007 (0.0008)
ΔTRADEY	−0.0003 (0.0004)	−0.0008 (0.0005)	−0.0001 (0.0005)	−0.0008* (0.0005)
ΔDCPY	−0.0005 (0.001)	9.95e−06 (0.0011)	−0.0003 (0.0011)	−0.0002 (0.0010)
ΔODAY	−0.0095 (0.0077)	−0.0020 (0.0018)	−0.0106 (0.0084)	−0.0013 (0.0008)
Hausman test (χ^2)	78.15 [0.0000]	78.15 [0.0000]	4.83 [0.4370]	4.83 [0.4370]
Number of countries	18	18	18	18
Number of observations	702	702	702	702

Dependent variable: lnRGDPPC. All equations include a constant country-specific term. Values in () and [] are standard errors and probability values, respectively

***,**,*Significance at the 1, 5 and 10 % levels, respectively. In Model 1, the climate variables are in their natural logarithmic forms and hence the coefficients are interpreted as elasticities whereas the coefficients in Model 2 are interpreted as semi-elasticities

consistently, negative and significant in the two estimators and in the alternative models. These convergence coefficients indicate that the model does not return immediately to its equilibrium state after a shock pushes it away from the steady state. The significance of the error correction terms provides further evidence of the existence of a long-run relationship. The magnitudes, thus, suggest significantly different short-run dynamics.

The PMG estimation results reveal an unanticipated long-run relationship between temperature and economic growth, albeit not statistically significant in model 1. The same can be said about precipitation in the long run. Including the quadratic terms of the climate variables, however, rendered the coefficients of temperature and precipitation significant. However, in the short run, temperature has a more pernicious effect on economic growth. Specifically, a percentage increase in temperature will significantly reduce economic performance in SSA by approximately 0.13 %, ceteris paribus. Precipitation appears to be correctly signed in the short-run model, albeit not significant. A possible conjectural explanation to the differing signs in the short- and long-run models could be adaptation. Thus, in the long run, countries might have adapted to the harsh conditions emanating from climate change. In the short run, however, the effect of climate change extemporaneously will be deleterious. In model 2, temperature is insignificantly deleterious to economic growth in the short run. However, the coefficient of the quadratic temperature term is positive and marginally significant. Thus, increase in temperatures will promote growth significantly to some level and thereafter will be detrimental. Specifically, the parameter estimates for temperature is positive (0.5330) while it is negative for the quadratic term (−0.0107). Thus, after 24.9 °C, the impact of temperature on growth is negative. In the long run, the effect of increasing temperatures on economic performance is reversed as approximately the latter is reduced by 11 % for a degree celsius rise in the former. The differing signs in the short and long runs affirm perhaps the need for inclusion of the quadratic terms of the climate variables. In a sense, however, temperature could be seen to have a "Laffer effect" on economic performance with respect to time in SSA. Stated alternately, temperature is beneficial to economic performance, but only to some point, after which its effect is injurious. The magnitude reveals that, economic performance significantly increases by 3 % for a degree celsius rise in temperature in the short run, ceteris paribus. The results further reveal that, precipitation does not significantly affect economic performance, whether or not we control for possible nonlinearities. The alternative estimators in the alternative models do not reveal any significant effect of precipitation on economic performance.

The results further reveal the importance of physical capital in enhancing growth as the coefficient of gross fixed capital formation appeared significantly positive. The other control variables do not seem to be significantly growth enhancing in SSA. As mentioned earlier, the results of the MG estimator are consistent with the PMG in terms of signs but not significance. The PMG estimator constrains the long-run coefficients to be equal or identical across the countries (i.e. homogenous), whereas the MG estimator allows the long-run coefficients to be country-specific (i.e. it reports the averaged responses). Thus, if the PMG estimator restriction ('poolability') is untrue, then the PMG estimates are inconsistent and the MG estimates are consistent in either case. We, therefore, use the Hausman test to test the validity of the "pooling" assumption to decide on the preferred specification. The test assesses whether the differences in long-run coefficients are not systematic (null hypothesis), and follows a Chi-square distribution with 6 degrees of freedom. The test results reported in Table 2 indicate a rejection of the null, thus refuting long-run homogeneity in model 1. Preference is therefore given to the MG estimates since the parameters are consistent, though not efficiently estimated. However, in model 2, the PMG estimator, the efficient estimator under the null hypothesis, is preferred.[8]

5 Concluding remarks

This paper is a contribution to the empirics of climate change and economic growth in Sub-Saharan Africa. Although substantial amount of academic research has been devoted to climate change, the overall effects on long-run growth are not conclusive. Moreover, the evidence pertaining to SSA is largely anecdotal and mainly confined to what research elsewhere has to say by extrapolation. An empirical appraisal of this topical issue is thus of concern to inform the direction of policy, and to position SSA properly in efforts aimed at mitigating the effects of global warming. In this paper, we estimate the effect of climate change on economic growth on a subset of SSA countries. The novelty of this work rests on varieties of empirical techniques thereby accounting for the nuances that are left out by extant studies. We also examine the long- and short-run implications of the relationship between climate change and growth. While the entire relationship is hard to pin down precisely, we are able to establish certain trends. Our results reveal an unanticipated long-run relationship between temperature and economic growth. This is true about precipitation in the long run. However, in the short run, we establish that temperature has a more pernicious effect on economic growth.

A possible conjectural explanation to the impacts in the short- and long-run models could be adaptation. Thus, in the long run, countries might have adapted to the harsh conditions emanating from climate change. In the short run, however, the effect of climate change could be deleterious. Specifically, a percentage increase in temperature significantly reduces economic performance in SSA by approximately 0.13 %, ceteris paribus. While this is in tandem with similar results on the relationship between climate change and growth in other regions, our results indicate that the relationship between real GDP per capita on one hand, and, its determinants on the other hand, and climate change (temperature and precipitation) is intrinsically nonlinear. This suggests that below a certain threshold level of annual mean temperature, increases in temperature boost growth performance in the long-run, all things being equal. After this threshold, increases in mean annual temperature tend to have damaging effect on long-run growth effort of SSA countries. Given that SSA relies heavily on the agricultural sector for the bulk of economic output, we surmise that higher temperatures could actually reduce agricultural output with ramifications for industrial growth, job creation and poverty reduction efforts.

[8] Including the quadratic precipitation term in the MG estimator posed estimation problems as the maximum number of iterations was exceeded. Consequent to the preference of PMG estimator over MG in model 2 and the non-significance of the precipitation coefficients in the other estimators, we deem it quite a commonplace to omit the quadratic precipitation term in the MG estimator.

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Appendix

Variable definitions

The data definition is taken mainly from the World Development Indicators (2010) of the World Bank and other relevant sources.

GDP (constant 2000 US$)

GDP at purchaser's prices is the sum of gross value added by all resident producers in the economy plus any product taxes and minus any subsidies not included in the value of the products. It is calculated without making deductions for depreciation of fabricated assets or for depletion and degradation of natural resources. Data are in constant 2000 US dollars. Dollar figures for GDP are converted from domestic currencies using 2000 official exchange rates.

CO_2 emissions (kt)

Carbon dioxide emissions are those stemming from the burning of fossil fuels and the manufacture of cement. They include carbon dioxide produced during consumption of solid, liquid and gas fuels and gas flaring.

Precipitation (millimetres)

This is the long-term average in depth (over space and time) of annual precipitation in the country. Precipitation is defined as any kind of water that falls from clouds as a liquid or solid.

Temperature: average temperatures in degrees celsius.

Labour force, total

Total labour force comprises people who meet the International Labour Organization definition of the economically active population: all people who supply labour for the production of goods and services during a specified period. It includes both the employed and the unemployed.

Gross fixed capital formation

Gross fixed capital formation (formerly gross domestic fixed investment) includes land improvements (fences, ditches, drains, and so on); plant, machinery, and equipment purchases; and the construction of roads, railways, and the like, including schools, offices, hospitals, private residential dwellings, and commercial and industrial buildings.

Official development assistance

Aid includes both official development assistance (ODA) and official aid. Ratios are computed using values in US dollars converted at official exchange rates.

Trade (% of GDP)

Trade is the sum of exports and imports of goods and services measured as a share of gross domestic product.

See Figs. 3, 4 and Tables 3, 4.

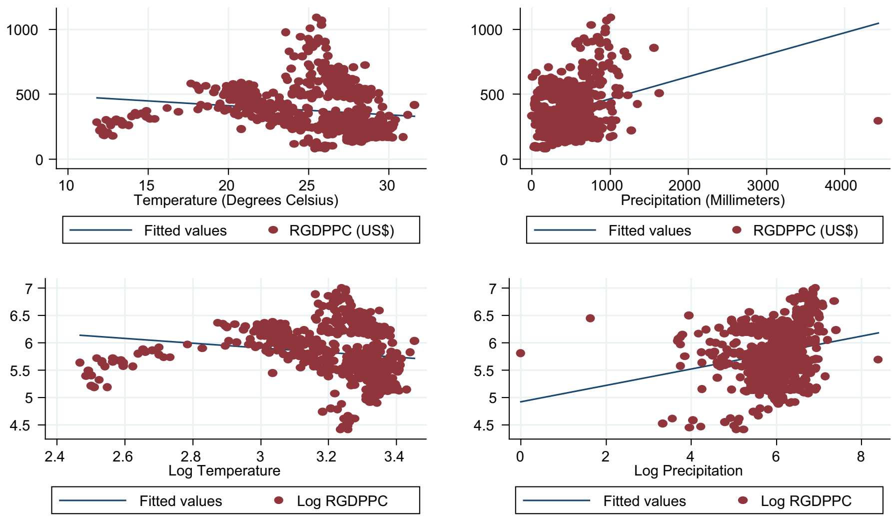

Fig. 3 Plot of real income and climate variables excluding South Africa

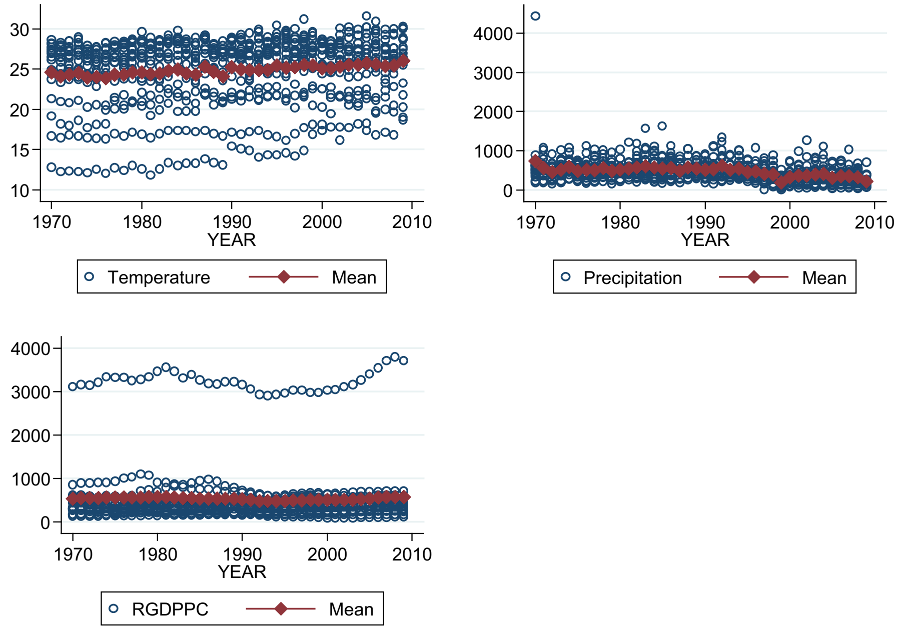

Fig. 4 Heterogeneity across years

Table 3 Panel unit root test results

Series name	Tests assuming a common unit root process			Tests assuming individual unit root process	
	LLC t*-stat H_0: unit root	Breitung t-stat H_0: unit root	Hadri Z-stat H_0: no unit root	IPS W-t-bar stat H_0: unit root	ADF-Fisher χ^2 H_0: unit root
Panel A: levels					
lnRGDPPC	−8.4045 [0.4338]	1.9497 [0.9743]	45.3896*** [0.0000]	−0.3599 [0.3594]	43.9097 [0.1714]
lnTEMP	2.2914 [0.9890]	−2.7203 [0.0033]	10.3629*** [0.0000]	−2.8507 [0.0022]	79.0921*** [0.0000]
lnPREC	2.7373 [0.9969]	−5.0016*** [0.0000]	14.6431*** [0.0000]	−4.0689*** [0.0000]	76.0237*** [0.0000]
lnGFCF	0.6920 [0.7555]	−2.6415*** [0.0041]	31.2803*** [0.0000]	0.2613 [0.6031]	28.2928 [0.8166]
lnTRADEY	−0.2311 [0.4086]	−1.5333* [0.0626]	28.5236*** [0.0000]	−0.9161 [0.1798]	37.9964 [0.3785]
lnDCPY	0.9356 [0.8353]	0.3888 [0.6513]	43.7904*** [0.0000]	1.3770 [0.9157]	22.8085 [0.9751]
lnODAY				−2.4819*** [0.0065]	59.6103*** [0.0080]
Panel B: first differences					
ΔlnRGDPPC	−10.9288*** [0.0000]	−7.9461*** [0.0000]	−4.3291 [1.0000]	−6.4770*** [0.0000]	127.3653*** [0.0000]

Table 3 continued

Series name	Tests assuming a common unit root process			Tests assuming individual unit root process	
	LLC t*-stat H_0: unit root	Breitung t-stat H_0: unit root	Hadri Z-stat H_0: no unit root	IPS W-t-bar stat H_0: unit root	ADF-Fisher χ^2 H_0: unit root
ΔlnTEMP	−12.9053*** [0.0000]	−6.6403*** [0.0000]	−4.2278 [1.000]	−9.3756*** [0.0000]	185.8590*** [0.0000]
ΔlnPREC	−12.3109*** [0.0000]	−8.3369*** [0.0000]	−4.4162 [1.000]	−13.4401*** [0.0000]	295.9278*** [0.0000]
ΔlnGFCF	−12.0850*** [0.0000]	−10.2696*** [0.0000]	−2.2269 [0.9870]	−7.0161*** [0.0000]	131.5479*** [0.0000]
ΔlnTRADEY	−11.9205*** [0.0000]	−8.8347*** [0.0000]	−1.0370 [0.8501]	−5.3102*** [0.0000]	101.3284*** [0.0000]
ΔlnDCPY	−9.8149*** [0.0000]	−9.4637*** [0.0000]	7.9384*** [0.0000]	−4.1601*** [0.000]	81.6705*** [0.0000]
ΔlnODAY				−6.0199*** [0.0000]	128.3614*** [0.0000]

*,*** Significance at 10 and 1 % levels, respectively. Test results on lnODAY for LLC, Breitung and Hadri tests are missing since these tests require strongly balanced data. This is as a result of data on this variable missing for South Africa from 1970 to 1992 possibly due to the Apartheid System, no official development assistance was received

Table 4 Panel cointegration test results

Pedroni's cointegration test

	Statistic	*p* value	Weighted statistic	*p* value
Common AR coefficients (within-dimension)[a]				
Panel v	−3.945144	1.0000	−3.482305	0.9998
Panel rho	1.997433	0.9771	1.933633	0.9734
Panel PP	0.753177	0.7743	−0.599430	0.2744
Panel ADF	1.024952	0.8473	0.151456	0.5602
Individual AR coefficients (between-dimension)[a]				
Group rho	2.7319	0.9969		
Group PP	−1.6678**	0.0477		
Group ADF	−1.4338*	0.0758		
Kao residual cointegration test[b]				
Test statistic = −1.692615** [0.0453]				

Fisher cointegration test

Null hypothesis	Trace test	*p* value	Maximum eigenvalue	*p* value
$r = 0$	154.3	0.0000	107.1	0.0000
$r \leq 1$	72.78	0.0003	43.29	0.1881
$r \leq 2$	61.94	0.0046	46.39	0.1150
$r \leq 3$	47.91	0.0885	35.56	0.4892
$r \leq 4$	41.96	0.2283	32.26	0.6471
$r \leq 5$	59.86	0.0075	59.86	0.0075

Test results were generated by Eviews 7. Pedroni's Panel statistics are weighted. The null hypothesis for all tests is that there is no cointegration

*,** Significance at 10 and 5 %, respectively

[a] The alternative hypothesis for the Pedroni cointegration tests

[b] There is no deterministic trend; automatic lag length selection based on SIC with a maximum lag of 3

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