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Inequality and Growth Impacts from Climate Change—Insights from South Africa

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Abstract

The impact of climate change on economic growth has received considerable attention in recent years based on several macro-econometric studies estimating the impact of country-level temperatures on GDP growth rates. We build on this literature, but instead of per-capita GDP, we consider inequality and poverty at the country and sub-national panel level with a focus on South Africa. Our analysis on both scales suggest a significant ∪-shaped relationship between inequality/poverty indices and local mean temperature. Inequality, hence tends to be lowest at moderate temperatures (11°C-17°C). Based on the Sen/Foster welfare function, we show that global warming hence has two detrimental effects in hot countries; reducing average growth, which dominates, and increasing inequality. Based on the moderate RCP4.5 projection, our results suggest an increase of the Gini index by three to four points compared to scenario without warming. Combined with the impact on GDP growth, this means a possible welfare loss of about 25% compared to the reference case without climate change.

Keywords: Inequality, climate change, income distribution, poverty

1. Introduction

Climate change impacts on economic outcomes, populations, and demographic groups have yet to be fully understood. Rising temperatures have been shown to have an impact on economic growth (Dell et al., 2009, 2012; Burke et al., 2015b; Newell et al., 2018), annual income (Deryugina and Hsiang, 2014), labor productivity and supply (Graff Zivin and Neidell, 2014; Antonelli et al., 2020), human capital (Graff Zivin et al., 2018), demography (Casey et al., 2019), migration (Desmet and Rossi-Hansberg, 2015; Shayegh, 2017; Cattaneo et al., 2019), food security (Deschênes and Greenstone, 2007; Antonelli et al., 2020), and energy consumption (Isaac and Van Vuuren, 2009; De Cian and Wing, 2019). The general conclusion of these studies seems to suggest that a) climate change is indeed a determining factor in shaping the future of human societies and b) the scale and direction of the climate change impacts vary by geographical and socioeconomic conditions. For example, historical increase in temperatures are shown to substantially reduce economic growth in poor countries through a wide range of impacts from reducing

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agricultural output (Jones and Thornton, 2003) to destabilizing political systems (Bosetti et al., 2020; Burke et al., 2015a).

Across countries, overall economic productivity seems to exhibit a non-linear relationship with annual mean temperature, with a peak at a temperature of 13.6°C and declining sharply beyond it (Burke et al., 2015b). However, the extent to which these impacts affect individuals within countries differently is still unknown. Several studies have shown that such impacts are highly asymmetric with more vulnerable populations in poorer developing countries of the south being affected more negatively than rich people in developed countries of the north (Hallegatte and Rozenberg, 2017; Kalkuhl and Wenz, 2018). However, these findings have been challenged by recent studies that show they hold only for mild temperature changes, while under more extreme climate projections, rich/cold countries will suffer more than hot/poor countries (Kahn et al., 2019). Such inconsistency in the climate change impact literature at global scale calls for more detailed and local analysis of climate change damages specially for developing parts of the world where adaptation measures are absent or deemed insufficient (Mendelsohn, 2008; Mirza, 2003). Moreover, combining the macro and micro findings is still a conceptual challenge.

Climate change also has been found to reduce welfare (Donadelli et al., 2017) and increase inequality within and between communities (Hsiang et al., 2019). In terms of its impact on income, a study of sub-national data from 12 countries in the Americas has found an overall negative relationship between temperature and income within countries, as well as across countries (Dell et al., 2009). At the global level, studies of economic inequality show that climate change exaggerates between-country inequality (Diffenbaugh and Burke, 2019). However, most of these studies have used global aggregated data on economic growth and temperature (King and Harrington, 2018); in particular, only limited broad evidence has been found with regard to within-country inequality and its link to weather/climate, with a few exceptions such as de Laubier Longuet Marx et al. (2019) and Sedova et al. (2019).

This paper contribute to filling this gap by providing a three-level analysis of the impact of climate change on income distribution and inequality using global, regional, and household panel data. Over the past few years, a number of national (e.g. National Income Dynamics Study (NIDS) in South Africa (Leibbrandt et al., 2009) and international household surveys (e.g. DHS by USAID (Rutstein and Rojas, 2006) and LSMS by the Word Bank (Grosh and Muñoz, 1996) have been continuously conducted throughout the world to cover the knowledge gap in the understanding of socioeconomic dynamics of local communities and their economic behavior at household level. This type of data can be used in combination with weather variables to provide the joint assessment of growth and inequality effects of temperature change from a micro bottom-up perspective.

Here we use longitudinal data from five waves of NIDS conducted from 2008 to 2017 in South Africa to study the impact of temperature change on income inequality. South Africa has experienced a widespread increase in local and regional temperatures over the last few decades (Kruger and Shongwe, 2004). Analyzing NIDS survey data in the past has revealed the non-uniform impact of climate change on the livelihood of local communities in South Africa specially on the most vulnerable groups such as specialized crop farmers in rural areas (Tibesigwa et al., 2015; Turpie and Visser, 2013). Furthermore, climate shocks such as long lasting droughts have increased food inequality among small vulnerable farming communities (Satgar and Cherry, 2020; Baudoin et al., 2017). In other words, climate change may exacerbate the existing widespread inequality (Hundenborn et al., 2018) and pervasive poverty

(Finn and Leibbrandt, 2017) in South African society.

Figure 1 (left-panel) shows the historical trend of rising annual mean temperature and inequality in South Africa, while the box-plot (right-panel) portrays the Gini coefficient and the mean temperature across the five waves of the survey data from South Africa used in this paper.

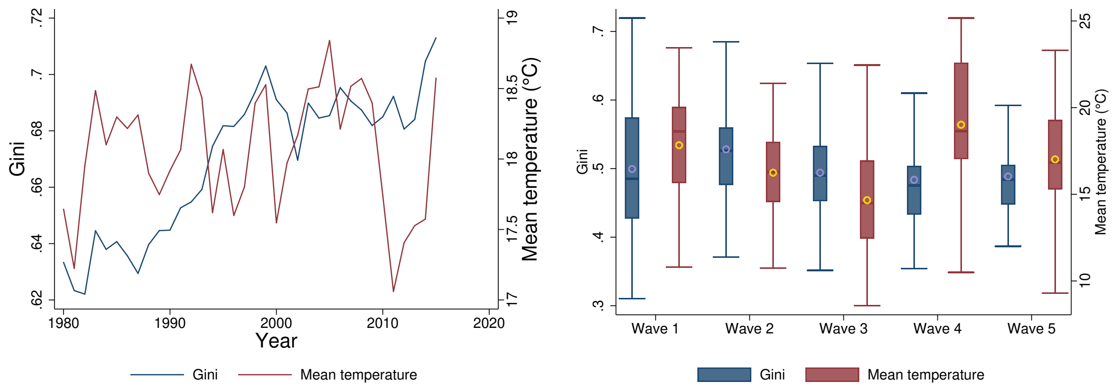

Figure 1: Inequality (NIDS) and annual mean temperature (ERA5) in South Africa.

2. Conceptual framework

We follow the approach of (Burke et al., 2015b) (BHM henceforth) to estimate the non-linear relationship between mean temperatures and our economic outcome variables (Δy_{it}). We focus only on temperature[1]. The response function of country n to temperature changes based on the country-level temperature $T_{n,t}$ is denoted by $h(T_{n,t})$ and can be defined in the quadratic case as;

$$h(T_{n,t}) = \tau_1 \; T_{n,t} + \tau_2 \; T_{n,t}^2. \tag{1}$$

Therefore, the warming impact $h(T_{nt})$ can be added to the reference scenarios without climate impacts of the variable y_{it}. In the case where y_{it} represents the logarithm of GDP per capita (or that Δy_{it} measures GDP growth), we can compute and simulate impact of climate using this formula;

$$GDPpc_{n,t} = GDPpc_{n,t-1} \underbrace{(1 + g_{n,t} + (h(T_{n,t}) - h(T_{n,0}))}_{e^{\tilde{g}}} \tag{2}$$

where $e^{\tilde{g}}$ is the growth factor including climate impacts or $\tilde{g}$ its growth rate. This result shows the effect of temperature on GDP per capita in a given country. If we want to look at the distribution within a country, on the other hand, we consider inequality indices such as the Gini index or the Atkinson measure $A(\eta)$ of inequality (Atkinson, 1970), or the class of Generalized Entropy Indices or the poverty headcount ratio P_0, which measures the proportion of the population that is counted as poor.

Given that these indies are typically defined on a bounded interval, e.g. between 0 and 1 for both Gini, Atkinson, and the Generalized Entropy indices, estimating growth rates would not be suitable. First, the index could grow without bounds and second while GDP growth rates are stationary, this is not true for the growth

[1]We did also consider precipitation but the results were never statistically significant and hence were omitted.

rate of such inequality measures. Hence, we considered the absolute change of the index as dependent variable, i.e., ($\Delta y_{it} = \Delta Gini_{it}$). Alternatively, we derive an "equality index" based on the Sen/Foster welfare function Sen (1973) given by $W = GDPpc(1 - G)$ or by Sen and Foster (1997) using Atkinson's concept of the equally-distributed equivalent level of consumption, c_{EDE} based on (Atkinson, 1970) similarly computed as $W = GDPpc_{n,t}(1 - A(\eta)_{n,t})$. Hence, subtracting the inequality index from one yields an equality index which multiplied by GDP per capita yields an easy to interpret welfare value in monetary terms.

While BHM consider the growth rate of per-capita GDP (the first term in this welfare function), we can estimate the growth rate of the second term $(1 - G)$, or that $\Delta y_{it} = \Delta ln(1 - Gini_{it})$ which allows us to compute the adjusted growth rate $\tilde{i}$ of this equality index, so that the growth rate of the welfare function will be the sum of both growth rates. That is $We^{\tilde{x}} = GDPpc_{n,t}e^{\tilde{g}}(1 - G)e^{\tilde{i}}$ and hence the growth rate of welfare $\tilde{x}$ is equal to $\tilde{x} = \tilde{g} + \tilde{i}$ and hence can be decomposed in the growth and equality improvement term.

2.1. Econometric model

We use the following econometric framework to investigate the impact of temperature on different dependent variables y_{it} including (logarithm of) income or GDP, inequality measures (Gini, Atkinson, and Generalized Entropy indices) and poverty indices (P_0, P_1, and P_2).

Note that we consider different units of observation, notably country as well as district, household, and individual-level data for South Africa. We define the first difference of the dependent variable (Δy_{it}) as in (Burke et al., 2015b);

$$\Delta y_{it} = \tau_1 T_{it} + \tau_2 T_{it}^2 + \beta \boldsymbol{X}_{it} + \alpha_i + \gamma_t + \epsilon_{it} \tag{3}$$

Dependent variable (Δy_{it}) is thus the change in y_{it} in country/district/household/individual i in year/wave t. We control for annual temperature T_{it} and its squared-term to capture potential non-linear effects. Inequality may decrease due to initial increases in temperature, however, beyond a threshold, incremental increases in temperature may result in increased inequality. Thus, it is expected that for the set of coefficients of temperature, $\tau_1 < 0, \tau_2 > 0$. For this case, the results indicate a non-linear relationship with an "optimal" value of temperature computed as $T^{opt} = |\tau_1/(2\tau_2)|$.

The term $\boldsymbol{X}_{it}$ is the matrix of other relevant country/district-level control variables influencing income inequality including income per capita and rate of employment. We also include district level (α_p) fixed-effects capturing all time-invariant attributes affecting income inequality. These fixed-effects allow us to identify the effects of annual temperature with the plausibly exogenous variation in temperature over time within countries/districts and within years. The term γ_t represents wave fixed-effects, while finally ϵ_{it} is a random error-term.

With regard to the climate date, we use reanalysed climate data from ERA5, the fifth generation ECMWF atmospheric reanalysis of the global climate. The data is available at a spatial resolution of 0.25°× 0.25°and hourly temporal resolution (C3S, 2017).

3. Global analysis of temperature and inequality

First, we estimate the response function of country-level Gini index to warming by fitting a non-linear curve to the observed data from year 1990 to 2016. The results of the statistical model are shown in table 1. Figure 2 shows that country-level

Gini index is smooth, non-linear, and convex in temperature, with a minimum at approximately 11°C. Interestingly this is below the 13°C peak reported for economic productivity by (Burke et al., 2015b). This result suggest that cold-country productivity increases while the inequality decreases as annual temperature increases, until the Gini optimum of 11°C is reached. From 11°C to 13°C we observe improving productivity at the cost of rising inequality. Productivity declines gradually after 13°C with further warming and with it, inequality grows at a faster pace than before. However, as evident from figure 2, global inequality is only mildly sensitive to temperature changes. Therefore, a more in-depth analysis at the regional and local scale is necessary to entangle the link between climate change and inequality.

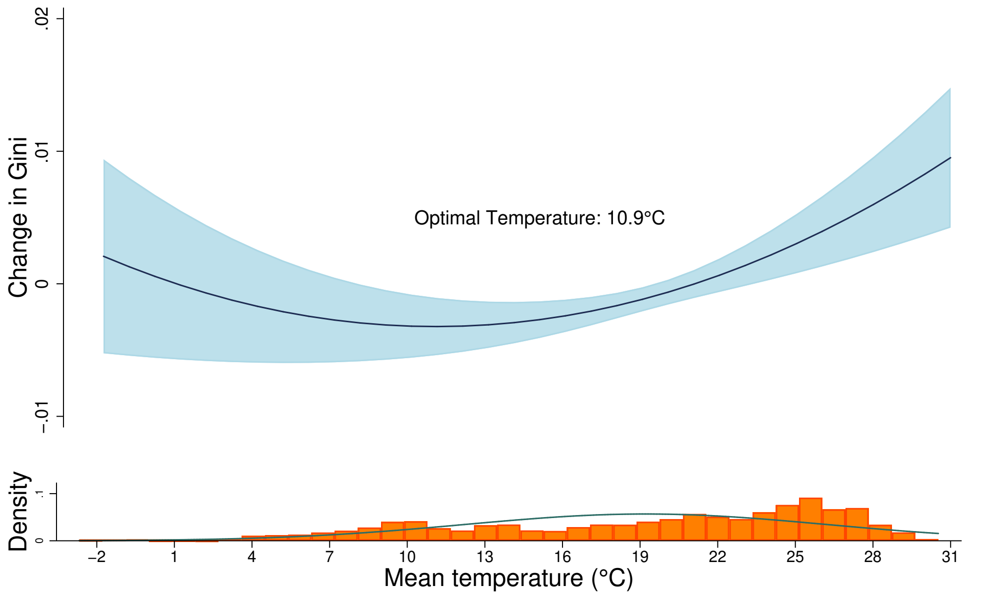

Figure 2: Global non-linear relationship of temperature - inequality.

Table 1: Global inequality regression

	(1)
	Δ Gini
Log of GDP	0.009***
	-0.005
Log of GDP-squared	-0.0004**
	-0.019
Mean temperature	-0.0006**
	(0.014)
Mean temperature-squared	0.00003***
	(0.000)
Constant	-0.4555***
	(0.001)
Observations	3,108
Number of countries	156
Robust p-values in parentheses	
*** p<0.01, ** p<0.05, * p<0.1	

4. Regional analysis of temperature and inequality

Next we turn our focus to a regional analysis of inequality with a particular focus on South Africa. South Africa is an interesting case of a developing country with large human capital and an atypical advanced economy for an African country. It also possesses a moderately warm climate that is affected by the currents of the surrounding oceans. We use gridded economic activity data from (Kummu et al., 2018) based on a resolution of 5 arcmin (about 9x9km at the equator) to investigate the impact of warming GDP/income per capita.

The results of the regional analysis of the impact of warming on GDP per capita is shown in table 2 and figure 3. The results support previous findings on a ∩ a non-linear relationship between temperature and GDP per capita change. As South Africa has a warmer climate compared to the global average, the optimal temperature is estimated to be approximately 15.6°C. However, not all areas of South Africa experience the same impact.

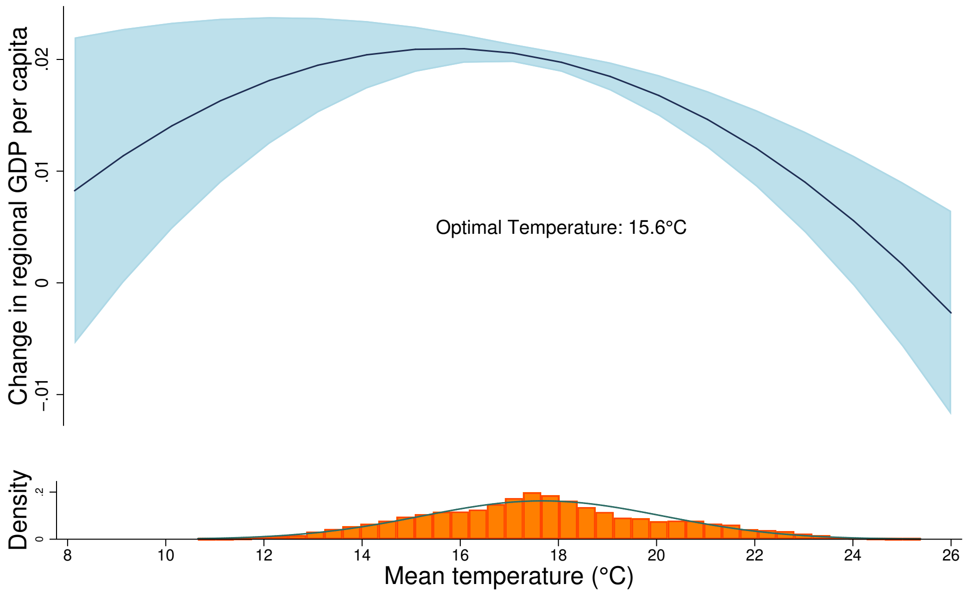

Figure 3: Non-linear relationship of temperature - income in South Africa.

Table 2: South Africa income per capita regression based on gridded data

	(1)
	Δ Income per capita
Mean temperature	0.0069***
	(0.003)
Mean temperature-squared	-0.0002***
	(0.000)
Constant	-0.0487**
	(0.021)
Observations	10,452
Number of grid-cells	419
Robust p-values in parentheses	
*** p<0.01, ** p<0.05, * p<0.1	

We can also use the spatially gridded data to compute a spatial Gini index for each district using gridded economic activity data from (Kummu et al., 2018). Obviously, this method grossly underestimates the full income distribution but provides a first dive into within-regional inequality based on spatial data. We run the specification in 3 controlling for log of income, mean temperature, and their second-degree polynomials. We find that the relationship between temperature and spatial Gini is ∪-shaped, similar to our findings from the global results for the Gini index (2).

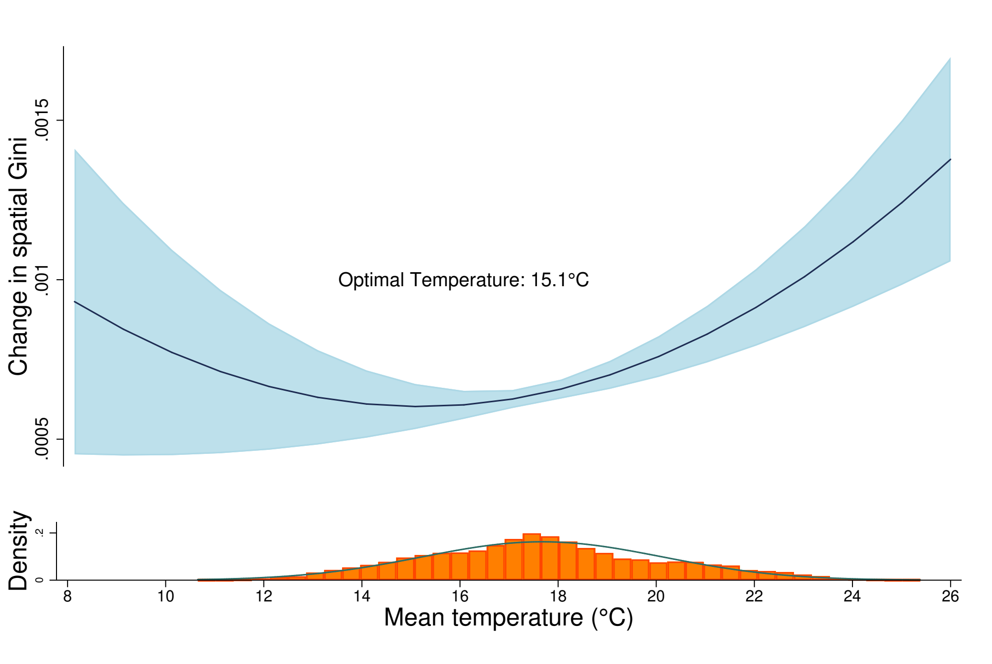

Figure 4: Non-linear relationship of temperature - spatial inequality in South Africa.

Table 3: South Africa spatial Gini regression based on gridded data

	(1)
	Δ Spatial Gini
Log of GDP	-0.0029***
	(0.000)
Log of GDP	0.00007***
	(0.000)
Mean temperature	-0.0002**
	(0.013)
Mean temperature-squared	0.000007***
	(0.002)
Constant	0.030***
	(0.000)
Observations	208
Number of districts	52
Robust p-values in parentheses	
*** p<0.01, ** p<0.05, * p<0.1	

Overall, the spatial data analysis for South Africa confirms the global results of a ∪-shaped relationship for the Gini and ∩-shaped for GDP per capita. Looking at the respective coefficients, it is clear that the magnitude are about an order of magnitude lower given that the spatial details is still very coarse at 5 arcmin. But the findings confirm macro results so far, so now we move to our main analysis of household panel data on the same subject.

5. Micro-based analysis of temperature and inequality

We now proceed to use household micro-data from a nationally representative longitudinal survey data in South Africa to investigate the impact of warming on income inequality looking at the district level. We focus on the impact of annual mean temperature on various measures of inequality. Increased temperature has been shown to increase inequality at the global level (Diffenbaugh and Burke, 2019). However, there is a lack of micro based evidence on the impact of temperature on income inequality.

The data comes from five waves (2008 to 2017) of NIDS conducted by the Southern Africa labor and Development Research Unit (SALDRU) based at the University of Cape Town[2]. This is the first nationally representative panel study of households in South Africa and uses a stratified, two-stage cluster sample design to sample households in the nine provinces of the country. NIDS primarily examines the livelihoods of individuals and households over time and provides information coping with shocks and includes detailed information on poverty and well-being, fertility and mortality, migration, economic activity, human capital, health, education, and social capital (see Appendix section A1 for more information on NIDS).

First we look at income per capita replicating the cross-country analysis of Burke et al. (2015a) (BHM) using Equation 3 with household income per capita data (South Africa Rand - ZAR) before taxes and transfers and adjusted for working members in a given household computed from the five waves of NIDS aggregated to the district level using sampling weights. Regression results suggests a similar pattern to the BHM global pattern and the gridded results reported in section 4. The optimal temperature for household income per capita growth in South Africa is estimated at 16.8°C.

Table 4: South Africa household income per capita regression based on NIDS

	(1)
	Δ Household income per capita
Mean temperature	5.769**
	(0.036)
Mean temperature-squared	-0.172**
	(0.034)
Constant	-45.258**
	(0.037)
Observations	208
Number of districts	52
Robust p-values in parentheses	
*** p<0.01, ** p<0.05, * p<0.1	

Second, instead of focusing on district-level average income, we exploit the panel structure of the data and focus on the impact of temperature on monthly individual income in South Africa. We use the same specification in Equation 3, but using data from all waves at the individual level with household fixed-effects. Similar to the cross-country GDP results, we find a ∩-shaped relationship between monthly temperature and individual income with with a maximum value of 18.8°C.

[2]http://www.nids.uct.ac.za/

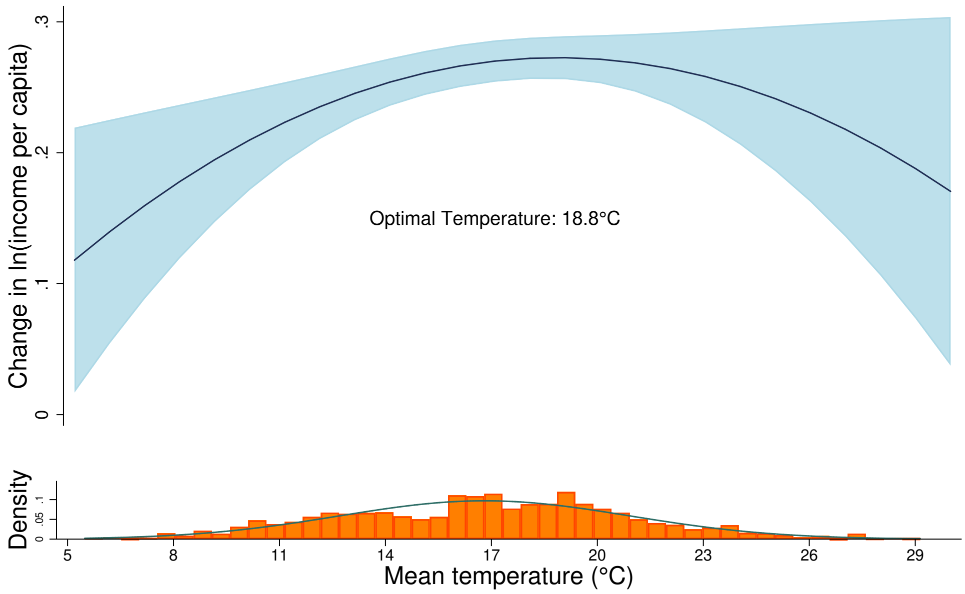

Figure 5: Non-linear relationship of temperature and individual income in South Africa.

Finally, we evaluate inequality based on individual level data aggregated at the district level. That is, we aggregate the individual responses from each wave of NIDS to the district-level in South Africa using individual weights from the fifth wave and estimate inequality indices using income responses over the five waves of NIDS. Figure 6 shows the spatial distribution of Gini index across South Africa over the five waves and suggests a substantial variation, both temporally and spatially.

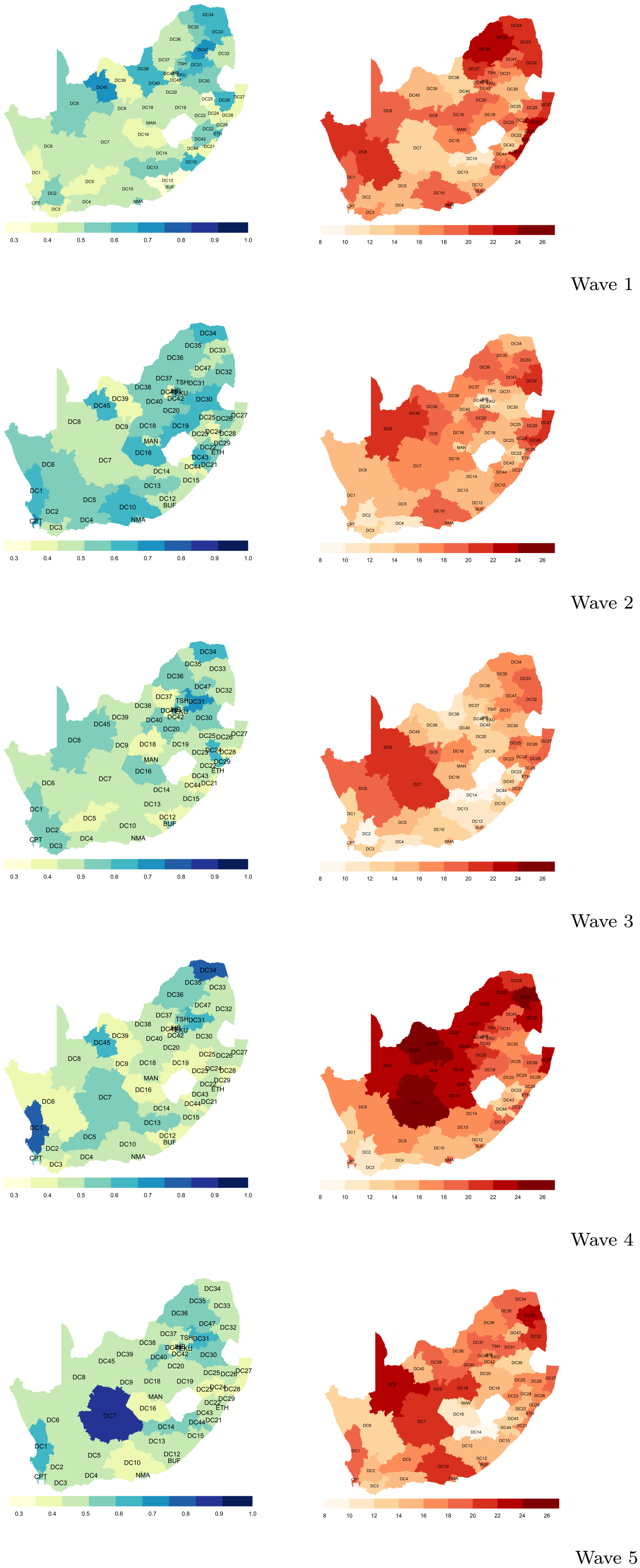

Figure 6: Gini coefficient by district in South Africa over five waves of NIDS.

Figure 6 shows the Gini coefficient and annual mean temperature across the 52 districts in South Africa. The plots suggest that there is significant heterogeneity in both inequality and climate across the country. The econometric results suggests that the temperature-inequality response functions are indeed also ∪-shaped (Figure 7), similar to exposure-response functions for the temperature mortality relationship (Dasgupta, 2018). Income inequality in South Africa is non-linear and convex in mean temperature and is minimal (T^{opt}) at around 17 °C. These results suggest that while income inequality decreases with initial increases in temperature, beyond these thresholds, any increments in temperature results in an increase in inequality. Looking at the effect along the income distribution, we consider all deciles separately with a BHM specification and indeed find that poorer parts of the population seem to experience a more pronounces impact curve, which results in the inverse U shape for inequality, see Section Appendix E in the Appendix.

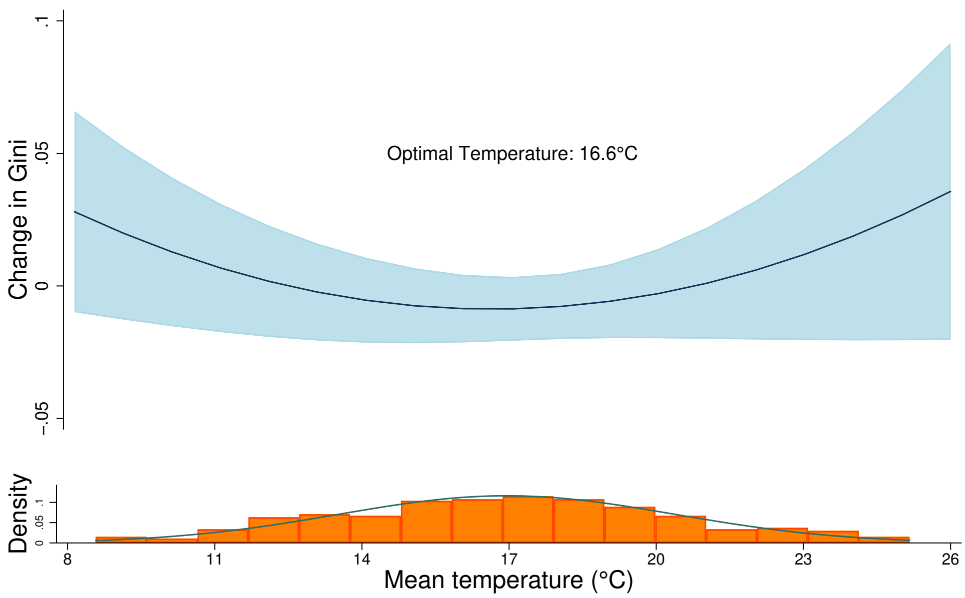

Figure 7: Non-linear relationship between temperature and income inequality (dark navy line) with 95% confidence interval (light blue area) at the district level in South Africa.

Table 5: Temperature - inequality regression results

	(1)	(2)	(3)
	Δ Gini	Δ GE(0)	Δ A(1)
Rate of employment	0.0282	0.0929	0.0578
	(0.736)	(0.518)	(0.528)
Log of income	0.2518*	0.5634**	0.3900**
	(0.087)	(0.034)	(0.012)
Log of income-squared	-0.0110	-0.0246*	-0.0170**
	(0.169)	(0.091)	(0.040)
Mean temperature	-0.0166**	-0.0279***	-0.0157**
	(0.014)	(0.007)	(0.042)
Mean temperature-squared	0.0005**	0.0008**	0.0005*
	(0.019)	(0.023)	(0.054)
Constant	-1.3083*	0.0000	-2.1178***
	(0.055)	-0.001	(0.003)
Observations	208	208	208
Number of districts	52	52	52
Robust p-values in parentheses			
*** p<0.01, ** p<0.05, * p<0.1			

Now, as discussed above, instead of the absolute change in the Gini index over time, we consider the growth rate in the equality index, that is we use as dependent variable Δln(1-Gini), which provides an intuitive measure of welfare in terms of equality. Moreover it restores the ∩-shaped of welfare and temperature found for economic growth, and allows to decompose the growth effect of GDP per capita and equality, see the next section.

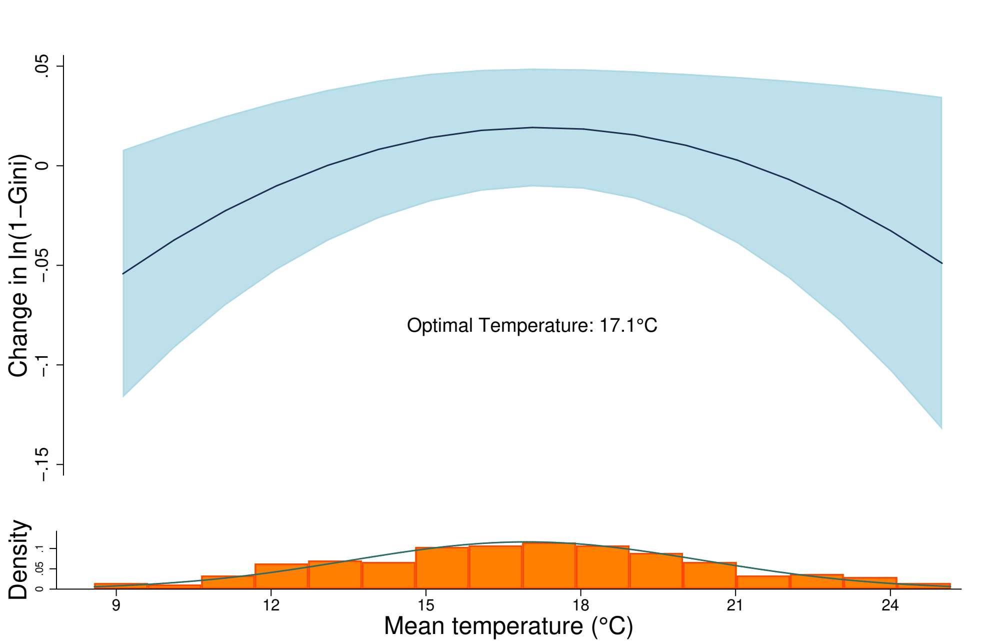

Figure 8: Non-linear relationship between temperature and growth in equality index (dark navy line) with 95% confidence interval (light blue area) at the district level in South Africa.

Table 6: Temperature and Δln(1-Gini)

	(1) Δln(1-Gini)
Rate of employment	-0.0558
	(0.740)
Log of income	-0.5222*
	(0.095)
Log of income-squared	0.0232
	(0.179)
Mean temperature	0.0322***
	(0.007)
Mean temperature-squared	-0.0009**
	(0.017)
Observations	208
Number of districts	52

Robust p-values in parentheses

*** $p<0.01$, ** $p<0.05$, * $p<0.1$

6. Inequality in South Africa in the 21st century

Based on the different specifications estimated, we can now proceed to simulate the effect of climate change on the Gini index in the future. We use a unified SSP-RCP scenario framework for projecting future socioeconomic and environmental changes in South Africa throughout the century. The SSP scenarios project five different outcomes abased on different approaches to sustainability, human capital development, and migration (O'Neill et al., 2017).
SSP1 is the sustainability scenario with a medium level of migration and high levels of low-emission technologies development and deployment. Countries enjoy higher rates of education and human capital accumulation and inequality is reduced both across and within countries.
SSP2 is the middle of the road scenario with a medium level of migration where the world follows a business-as-usual development path. Global population grows moderately while there will be slow improvements in income inequality and environmental challenges.
SSP3 represents a world filled with regional rivalry with a low level of migration and a decline in investments in education and technological development. Slow economic development coupled with high population growth in developing countries exert large pressure on natural resources and environmental indicators.
SSP4 is the inequality scenario with medium levels of migration where economies are growing in different rates across the globe. The world will be divided between highly educated societies with access to high technologies and capital and resources and lower-income, poorly educated societies with low-tech economy.
SSP5 represents a world with a high level of migration where economic development is closely tied to high fossil-fueled consumption. Technological progress is rapid and human capital grows fast. Investments in health, education, and institutions increases as global population peaks and declines in the 21st century.

For the climate change projections we adopt different pathways to greenhouse gasses concentration (Van Vuuren et al., 2011). The four RCP scenarios (RCP2.6, RCP4.5, RCP6.0, and RCP8.5) correspond to the projected level of radiative forcing in 2100. Moreover, we show the results for the Reference projections without climate change ("Reference case"). We consider in particular the climate model trajectories RCP2.6 and RCP4.5 across all models as ensemble mean, which indicates an increase in the annual average temperature in South Africa from 17.97°C in 2018 to 19.6°C by 2100 in RCP4.5. Based on the empirical specifications for $\Delta Gini$ in equation 3, we can thus evaluate the change in the Gini index from the reference projection based on a growth rate of the equity index as

$$1 - Gini_{it} = (1 - Gini_{it-1})(1 + g_{it}^{GiniRef} + (\tau_1 T_{it} + \tau_2 T_{it}^2) - (\tau_1 T_{i0} + \tau_2 T_{i0}^2)) \quad (4)$$

In the "Reference" case, the growth rate of the equality index $g_{it}^{GiniRef}$ is calculated from the reference Gini projections depending upon the socioeconomic changes of each SSP scenario. For example, GDP per capita in 2100 ranges from 14,300 to 44,000 US-$[2005] across SSPs while Gini index varies from 0.49 to 0.65 depending on productivity and educational developments among others (Rao et al., 2018). We combine this projections with the historical data based on the Standardized World Income Inequality Database (Solt, 2016) to obtain consistent trajectories of South Africa's future welfare and inequality measures across SSPs.

For the overall inequality level, using the best specification estimates of $(\tau_1, \tau_2) = (0.0322, -0.0009)$, the top-left panel in Figure 9 shows the Gini index projections under RCP2.6 and RCP4.5 scenarios along with the Reference case without climate change. Under RCP4.5 scenario, the Gini index reaches 0.62 by 2100 in SSP2 which is higher than its values the "Reference" case indicating the role of climate change in increasing inequality. Across all SSPs, climate change (as defined by the difference between the results of RCP4.5 scenario and the "Reference" case) increases Gini index between 2.7 and 3.9 points by 2100. Note that under RCP2.6 scenario (i.e. global mean temperature increase stays below 2 degrees), the Gini index even slightly decreases compared to the "Reference" case without climate change.

Next, using the Sen/Foster welfare function and thus decomposing the growth impact on GDP per capita and inequality, we use the base case SR specification from BHM to project the equality index (top-right panel in Figure 9), GDP per capita (bottom-left panel in Figure 9), and finally the combined effects on the welfare (bottom-right panel in Figure 9). We make two main observations based on the results of these graphs. First, the GDP growth effect shows losses of around 20% of the GDP in the "Reference" case, consistent with Burke et al. (2015b) given the moderate RCP4.5 scenario. Second, climate change increases inequality significantly and varying across SSPs. As a result of these two observations, climate change is expected to reduce the welfare by around 25% of its value under the "Reference" case without climate change across SSP projections.

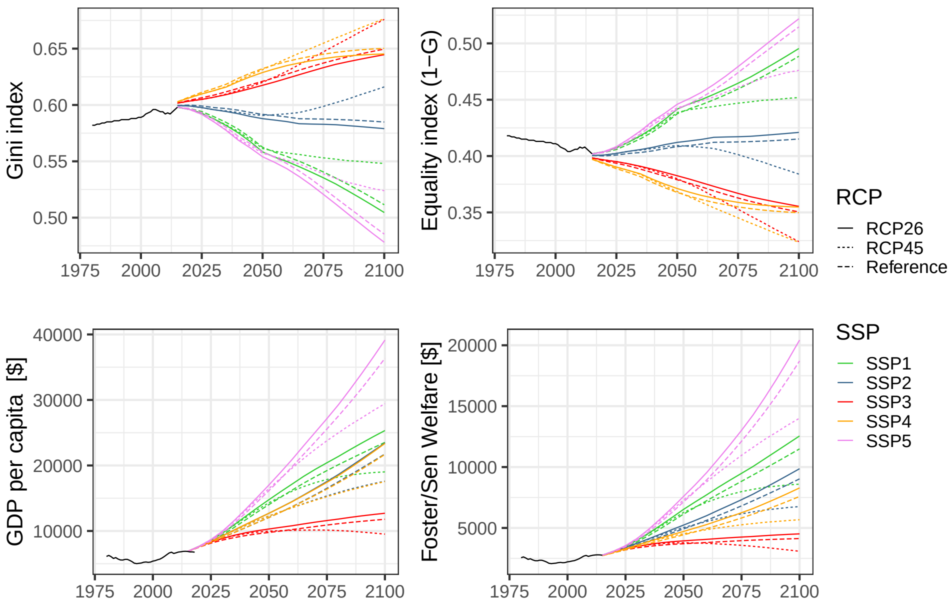

Figure 9: Projection of GDP per capita, equality, and welfare for South Africa decomposed.

7. Conclusion

Climate change not only affects the aggregate economic productivity but also has an impact on inequality and poverty. In this paper we address this link conceptually and apply it to the case of South Africa which suffers from an underlying pervasive inequality and widespread poverty.

Using data at multiple spatial scales (country, gridded, and household), first, we find that country-level Gini index is smooth, non-linear, and convex in temperature, with a minimum at about 11°C. Second, using gridded data and a nationally representative longitudinal National Income Dynamics Study, we estimate that GDP/income per capita is maximized at 15.6°C (gridded data) and 16.8°C (household survey data), respectively. Third, we investigate the impact of warming on inequality at the district level in South Africa. The results suggest that the temperature-inequality response functions are ∪-shaped, similar to exposure-response functions for the temperature-mortality relationship (Dasgupta, 2018). Income inequality in South Africa is non-linear and convex in mean temperature and is minimized at around 18°C.

Two main robust findings can be derived on these results; While GDP or income per capita shows a ∩-shaped relationship with temperature, inequality and poverty relationship with temperature is ∪-shaped. This observation holds for all three sources of inequality from macro aggregates to micro household data. In terms of the location of the extreme, we find that the optimal temperatures are lower for inequality measures than for income levels. This indicates that substantial increases in inequality are expected at higher temperatures compared to growth impacts starting already at lower temperature increases.It is worth mentioning that the average annual temperature in South Africa (17.97°C in 2018) is currently lies within this interval, indicating the potential for a short-term income gain from climate change in South Africa while the inequality outlook remains negative in long-run.

Finally, when we combine the results of our empirical analysis with climate scenarios, we observe that climate change under a moderate scenario of RCP4.5 could increase the Gini coefficient and poverty rate by about 3-4 percentage points compared to the "Reference" case without climate change or the mitigation-driven case of RCP2.6 across all SSP scenarios by the end of the century.

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Appendix A. Definitions

Appendix A.1. Inequality measures

1. Generalized entropy class: The general entropy (GE) class of inequality indexes is based on the concept of disorder. When applied to income distributions, entropy or disorder represents deviations from perfect equality based on a weight to distances between incomes in different parts of the income distribution. For the purposes of this paper, we set the weighting parameter (which measures aversion to inequality) equal to zero.
2. Atkinson inequality index: This index presents the percentage of total income that a society would have to forego in order to have more equal shares of income among its citizens. This measure depends on the degree of society aversion to inequality, where a higher value entails greater social utility or willingness by individuals to accept smaller incomes in exchange for a more equal distribution. We set the inequality aversion parameter equal to 1.
3. Gini index: This index measures the extent to which the distribution within an economy deviates from a perfectly equal distribution. The Gini index is based on the Lorenz curve, a cumulative frequency curve that compares the distribution of a specific variable (e.g. income) with the uniform distribution that represents equality.

Appendix A.2. Poverty measures

1. Headcount index (P_0): Measures the proportion of the population that is counted as poor.
2. Poverty gap index (P_1): This index adds up the extent to which individuals on average fall below the poverty line, and expresses it as a percentage of the poverty line.
3. Squared poverty gap index (P_2): This index considers inequality among the poor by using a weighted sum of poverty gaps (as a proportion of the poverty line), where the weights are the proportionate poverty gaps themselves; this is in contrast with the poverty gap index, where the gaps are weighted equally.

Table A.7: Descriptive statistics

Variables	Mean	Min	Max
Gini	0.50	0.31	0.89
P_0	0.37	0.03	0.88
P_1	0.17	0.01	0.57
P_2	0.10	0.00	0.41
Household income (ZAR)	7651.04	1886.74	71401.82
Household expenditure (ZAR)	3386.23	437.37	79116.52
Mean temperature (°C)	16.97	8.31	25.88

Appendix B. Alternative measures of inequality

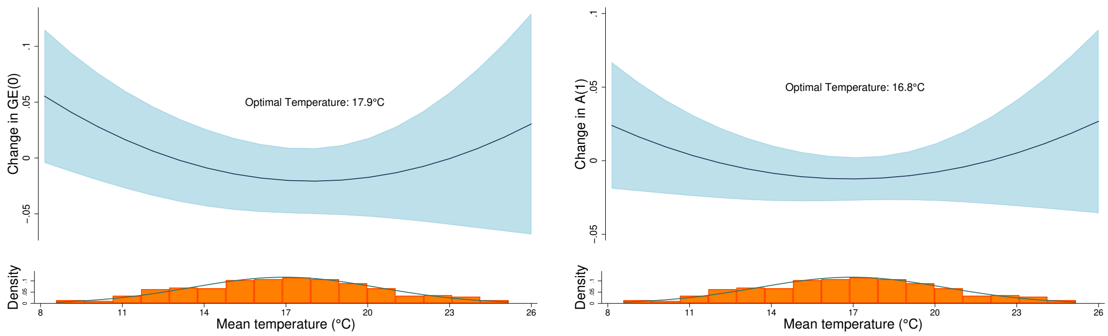

Figure B.10: Non-linear relationship between temperature and income inequality (dark navy line) with 95% confidence interval (light blue area) at the district level in South Africa. Specification also controls for income per capita, rate of employment, and district and wave fixed-effects.

Appendix C. Inequality estimation in levels for South Africa

Table C.8: Temperature - inequality regression results: level specification

	(1)	(2)	(3)
	Gini	GE(0)	A(1)
Rate of employment	-0.0923**	-0.1641**	-0.0778
	(0.048)	(0.041)	(0.165)
Log of income	0.1440**	0.3214**	0.2070***
	(0.034)	(0.010)	(0.009)
Log of income-squared	-0.0060*	-0.0134**	-0.0089**
	(0.097)	(0.044)	(0.032)
Mean temperature	-0.0167***	-0.0304***	-0.0189***
	(0.003)	(0.004)	(0.008)
Mean temperature-squared	0.0005***	0.0008***	0.0005**
	(0.004)	(0.006)	(0.011)
Constant	-0.1513	-0.8444	-0.4778
	(0.621)	(0.129)	(0.186)
Observations	260	260	260
Number of districts	52	52	52
Robust p-values in parentheses			
*** p<0.01, ** p<0.05, * p<0.1			

Appendix D. Temperature and poverty in South Africa

While the inequality indies used so far evaluate the full distribution of income, we can also focus on the issue of poverty, evaluating only individuals below the poverty line. Using several poverty indices as in , we also find a convex relationship between temperature and poverty in South Africa, similar to results obtained for the temperature-inequality relationship. We find that the mean temperature of minimal poverty is at 17°C for the headcount index (P_0), with higher values of 20.7°C for the poverty gap index (P_1), and 22.8°C for the squared poverty gap index (P_2)., suggesting that poverty is minimal at a higher temperature compared to inequality in South Africa. These results suggests that poverty declines with initial increases in temperature however, beyond the *minima*, increases in temperature results in increased poverty at the district-level in South Africa.

Table D.9: Temperature - poverty regression results

	(1)	(2)	(3)
	Δ P0	Δ P1	Δ P2
Rate of employment	0.047019	0.1908**	0.0809
	(0.507)	(0.038)	(0.164)
Log of income	0.7138***	0.7977***	0.7524**
	(0.000)	(0.000)	(0.000)
Log of income-squared	-0.0339***	-0.0396***	-0.0389***
	(0.000)	(0.000)	(0.000)
Mean temperature	-0.0226**	-0.0438***	-0.0285***
	(0.020)	(0.000)	(0.000)
Mean temperature-squared	0.0007**	0.0011**	0.0006**
	(0.038)	(0.010)	(0.017)
Constant	-3.7018***	-3.7299***	-3.4259***
	(0.000)	(0.000)	(0.000)
Observations	208	208	208
Number of districts	52	52	52

Robust p-values in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Appendix E. Temperature and income by decile

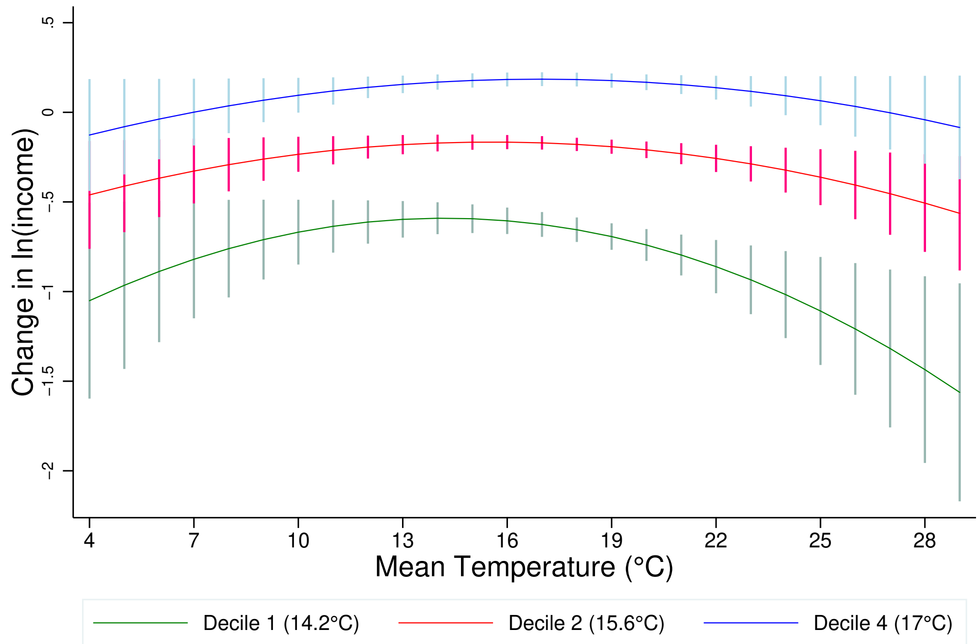

Figure E.11: Non-linear relationship between temperature and household income by decile with 95% confidence interval (spikes) in South Africa. Specification controls for education level of the household head, household expenditure, and household and wave fixed-effects.

Appendix F. Projection of the poverty rate

With regard to projection of the poverty rate, using the poverty rate of the World Bank at 1.90 USD per day (in 2011 prices), the baseline absolute poverty index (P_0) can be obtained from WDI. For the projections, different from the Gini no projections in the SSP framework are available yet. Hence, as a first approximation, we use the two parameter log-normal approximation of future SSP data matching

Gini and GDP per capita from the SSP projections and apply the estimates of climate change for the different RCPs. This will allow us to entangle the poverty impact of climate change as depicted in Figure F.12. Based on the BHM base specification SR and our baseline Gini projections, this figure shows the wide range of poverty development across SSPs and RCPs. With regard to the climate impact, we find increases in poverty notably when unfavorable socioeconomic conditions (SSP3 and SSP4) are combined with global warming. Yet these results as based only on two moments are to be taken with precaution and a more thorough analysis on poverty would be warranted.

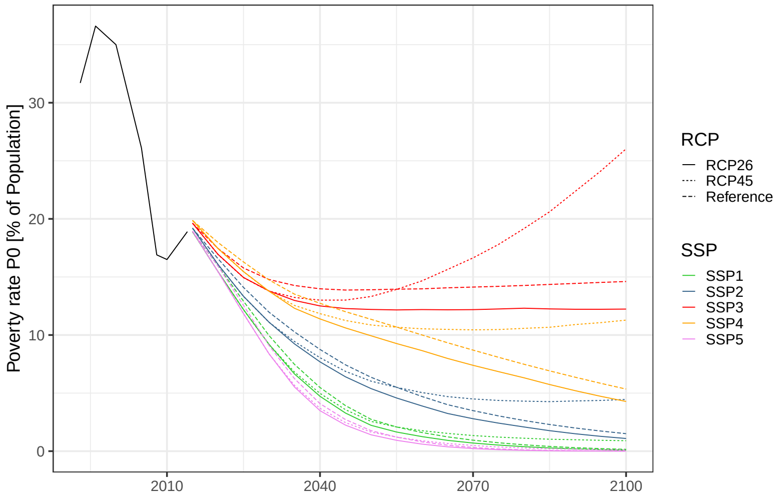

Figure F.12: Projection and of the poverty rate for South Africa.