Too hot, too dry and too wet for growth?

Macroeconomic risks of climate change and extreme-weather events in Africa.

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Abstract

Africa, despite high GDP growth in the last two decades, still displays the lowest level per capita globally. In fact, 34 out of the 48 Least Developed Countries are located in Africa. To progressively graduate these countries from the LDCs categories, income and GDP need to grow at a rate that allows the expanding population to access sufficient means of living. Fostering GDP growth in these countries is also in line with SDG#8 on decent work and economic growth. Climate-related disasters haven taken their toll on the continent, with increasing risks due to climate change, concerns arise with respect to the ability of African countries pursue economic growth in line with the SDGs and future graduation. Assuming the pledges of the Paris agreement were to be fully implemented, global mean temperature would still increase by about 3°C by 2100; and therefore would further change mean and extreme weather patterns on the continent. This research investigates how climate change in African countries will affect development trajectory between 2015 and 2050.

A growing body of literature has investigated the macroeconomic consequences of temperature changes globally (Burke, et al., 2015) and in African (Abidoye & Odusola, 2015). African countries are also largely affected by hydro-meteorological extremes, especially droughts and floods (Barrios, et al., 2010; Berg, 1976; Brown, et al., 2010). To encompass both these climate risk dimensions, a novel econometric approach was developed to estimate the sensitivity of macroeconomic indicators (GDP and sectoral value-added, here GDP per capita) to temperature and precipitation extremes. Using the data from Baarsch et al., (*forthcoming*), macroeconomic risks are estimated until 2030, consistent with the Sustainable Development Agenda, and 2050. The inferred sensitivities are used to appraise the projected effects of climate change in two warming scenarios (RCP2.6 and RCP8.5) based on climate projections from an ensemble of GCMs from the CMIP5 database (Hempel, et al., 2013).

The results show GDP growth could be lower by about 0.1 and 0.3 percentage point for all African countries in the 2015-2050 period. In the high warming scenario (RCP8.5). The frequency and intensity of extreme events leading to large decrease in GDP per capita growth significantly increase in the high warming scenario (RCP8.5). The analysis also finds that precipitation extremes play a significant role in the negative impacts of climate change in both scenarios, even though this share progressively decreases as temperature becomes the most notable driver of macroeconomic risk, especially in the high warming scenario.

In line with previous studies, this research indicates that future economic growth in African countries could be severely hampered by climate change and climate-related disasters. The study also shows that extreme wet and dry disasters have long-lasting consequences, significantly shifting downwards countries' development trajectories. This detailed analysis of the future consequences of climate change on African economies sheds light on four main conclusions relevant to the achievement of the SDGs in Africa: 1- the benefits of stringent mitigation action will be felt as early as the 2030s in African countries and even more later in the century; 2- current and future development planning needs to better integrate climate-related risks; 3- long-term adaptation planning has to account for the dynamicity of the economy, especially in African countries where structural change occurs at an accelerated rate; and finally 4- adequate disaster risk management tools (insurance, contingency funds and plans, development safety nets, etc.) need to be implemented and / or scaled-up to hasten the recovery process. Additionally, this research also provides ground to better quantify to the benefits of climate change adaptation and disaster risk reduction measures implemented in African countries.

Introduction

African countries' macroeconomic indicators are vulnerable to the effects of climate-related disasters (Abidoye & Odusola, 2015; Barrios et al., 2010; Dell, Jones, & Olken, 2012). Droughts in the Sahel in the 1970s have led to steep double-digit decrease in countries' GDP and agricultural value-added (Berg, 1976), notwithstanding the human and social consequences induced by these disasters owing to the large number of casualties incurred by the droughts as well as flooding events (CRED, 2015). With the heightening consequences of climate change in the coming years and decades, reaching the target of the SDG#8 of decent work and economic growth could become more challenging. Improving the scientific understanding of the consequences of climate-related disasters on the economic development of African countries in the coming decades is of significant importance for policy-planning in terms of development and adaptation to climate change at the national level as well as mitigation action at the global level. More specifically, the detailed analysis of the effects of different types of climate-related disasters, extreme hot, dry and wet provides relevant additional information to adequately plan adaptation and disaster risk management.
Hitherto, recent studies have mostly focused on the effects of temperature on macroeconomic indicators (Burke et al., 2015; Dell et al., 2012; Moore & Diaz, 2015), using precipitation either as a control variable or in some cases ignored. The objective of this study is to further capture the full impact of climate change on macroeconomic indicator at the country level, including by integrating the effects of precipitation-related climate extremes, extreme dry and wet events, which have been associated with very severe macroeconomic consequences in African countries.
This paper present findings from a macro-econometric based forecast model, which accounts for the non-linear effects of both precipitation extremes and temperature. The specific effects of each type of climate-related disasters are introduced separately, to further disentangle the consequences of different types of climate-related extremes and combined for each African countries between nowadays and the 2030s in the two different warming scenarios.

1. Data and methodology

The past and future effects of climate-related disasters and climate change on GDP at the country level is inferred from an macroeconometric-based forecast model. The model uses past and projected grid-level precipitation and temperature data as variables influencing multidimensional development. The guiding principle underlying the modeling is that precipitation events and temperature levels of same intensity will have effects of similar magnitude expressed in change in GDP per capita in the near future (until 2030 and 2050) as they had in the recent past (from 1980-2014). This econometrically-inferred development effect in relation to a given intensity of precipitation and temperature deviation to an historical mean, is called sensitivity – referring to the theory of climate analogues (S. Hallegatte et al., 2007).

Sensitivities are inferred using a piecewise multivariate regression model (Equation 1), which uses GDP per capita (), as dependent variable, and bins of precipitation intensity () as well as temperature variation against a historical mean noted as independent variables. The model also includes control variables (such as oil prices, government spending, external debt, etc. and a country-level time-invariant fixed effect (.

Equation 1

Precipitation intensity is defined using an index, which normalizes precipitation and allows for comparison from one country to another even though precipitation levels are of different magnitude. This study employs the Standardized Precipitation Index (SPI, Vicente-Serrano & López-Moreno, 2005). Exposure to bins of precipitation intensity is calculated by measuring the percentage of population-weighted area of a country, during a given year, exposed to a segment within the broader range of the index on a monthly basis (in the case of SPI, increment of 0.5 are used, between -2 and +2, with two additional bins for extreme values below -2 and above +2).

The projections up to 2030 and 2050 are realized using the sensitivity coefficients inferred by the regression model (for precipitation intensity and and for temperature levels) and exposure to the same range of precipitation intensity and temperature deviation using the grid-level bias-corrected projections of five Global Circulation Models from the Coupled Model Intercomparison Project Phase 5 (CMIP5) (Hempel et al. 2013). The development rollback risk is computed in two scenarios, the IPCC RCP8.5 scenario (called high warming in this study) and the IPCC RCP2.6 scenario (called low warming) from 2015 to 2030, in line with the Sustainable Development Agenda and 2050.

To better account for the future risks to which African countries are projected to be exposed to, the economic framework integrates the intensity of the climate-related disasters, the exposure of the countries to these disasters as well as their historical vulnerability:

- The consideration of the intensity of climate-related disasters is made possible by the use the gridded monthly precipitation and temperature for both historical and projections data;
- In the model, economic exposure is proxied by weighting the overall country exposure with population density, following the assumption that more densely populated areas produce higher economic output (Nordhaus, 2006);
- Country specific vulnerability is provided by the non-linear regression model, which measures the sensitivity of GDP per capita to various levels of precipitation intensity and temperature, following the concept of vulnerability curves largely used for other types of natural disasters (here the example of earthquakes: Rossetto & Elnashai, (2003)).

For every year, country, model (five GCMs from the CMIP5 database) and scenario (RCP8.5 and RCP2.6), the economic model produces 10 macroeconomic risk effect estimates for the period 2015-2050 (therefore 50 for every year, country and scenario). The results are presented for the following types of climate-related disasters (extreme hot, dry and wet) separately and combined for each African countries, for which historical and projection of socioeconomic indicators data are available[1].

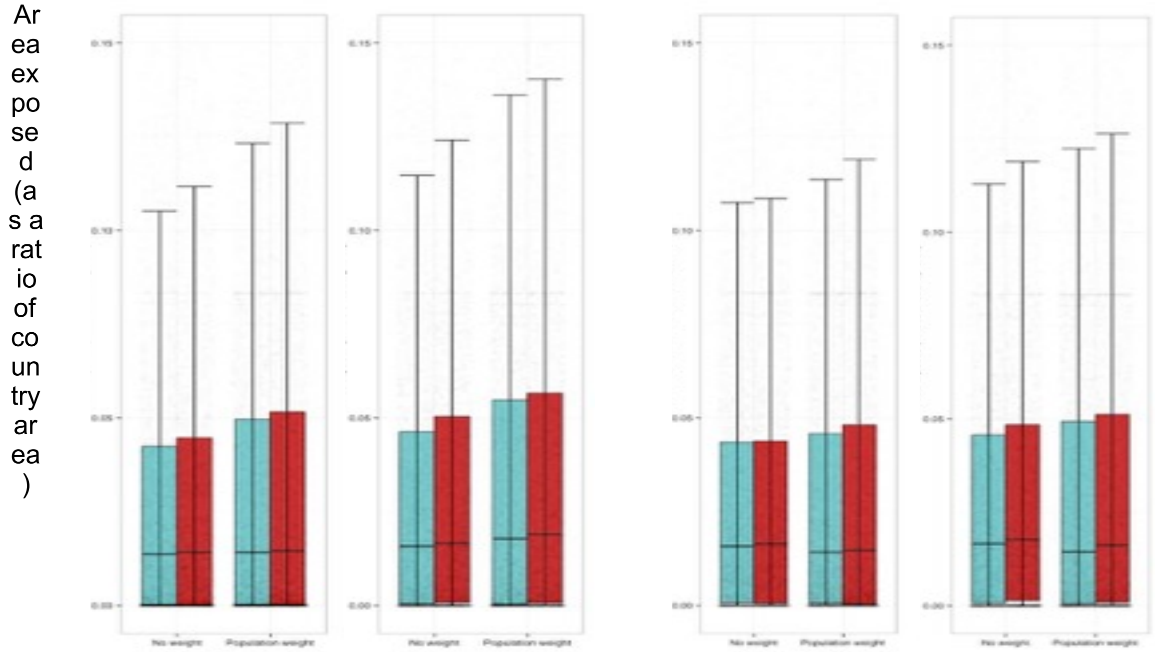
2. Raising exposure to climate-related extremes

Hydro-meteorological extremes are the extremes with the largest impacts on African economies. Barrios, et al., (2010) estimated that contemporary lower than historical rainfall could explain between 15 and 40% of the gap in GDP per capita between African countries and the rest of the developing world. Publications have shown that floods and especially droughts have led to significant drop in African countries' macroeconomic indicators (Berg, 1976).

In this section, the analysis focuses on the historical and projected exposure of African countries to the most extreme hydro-meteorological hazard, extreme dry or extreme wet. Hydro-meteorological extremes are determined using the Standardised Precipitation Index (SPI), for which monthly value is below -2 (extreme dry) and above +2 (extreme wet). To further understand the role of exposure, the shares of countries affected by climate-related extremes are population-density weighted (population weight in Figure 1) and unweighted (No weight in the same figure). In these settings, exposure is computed using population density as a proxy - consistently with findings from Nordhaus, (2006) following which accounting for population density in estimating the impacts of climate change could lead to two- to three times larger macroeconomic damages than a weighting based on output or area (Nordhaus, 2006).

[1] The analysis was conducted for 40 countries, satisfying socioeconomic and climate data availability.

The share of territory affected by extreme dry and extreme wet events is computed by applying the grid-level bias-corrected projections of five Global Circulation Models[2] from the Coupled Model Intercomparison Project Phase 5 - CMIP5 (Hempel et al. 2013) under the RCP2.6 and RCP8.5 scenarios (see methodological annex for additional details). The following **Figure 1**, displays the percentage of areas affected by extreme dry and wet events under the RCP2.6 (blue) and RCP8.5 (red) scenarios accounting for population density as a measure of economic exposure and without accounting for exposure.



Extreme dry events (SPI value below -2) Extreme wet events (SPI value above +2)

Figure 1 Population weighted and non-weighted area exposed to extreme dry events (in the left-hand side panel) in Africa in the period 2015-2029 (left) and in the period 2035-2050 (right). In the right-hand side panel, population weighted and non-weighted area exposed to extreme wet events in Africa in the same time periods. Authors' computation using Hempel et al., 2013 bias-corrected precipitation data.

The results of the analysis of the precipitation data from the five GCMs highlight the importance of population density when accounting for exposure to hydro-meteorological extremes. Even though the mean estimates are particularly close in both scenarios and with / without taking into account exposure for this period, the distribution of the more extreme values shows a higher exposure to of extreme dry and wet events when weighted future climate disaster risks with population density. This difference in the geographical spread of extremes is a fundamental element for both the regression analysis, which also integrates climate data exposure weighted based on population density and the future macroeconomic risks computation (Nordhaus, 2006).

3. Results

a. Optimal and extreme climates

Based on the regression model described above (data and methodology section), the study investigates the non-linear effects of different levels of precipitation intensity, from extreme dry to extreme wet events using the Standardized Precipitation Index (SPI) and of the deviation of temperature from the historical 1950-1980 mean. This approach combines different existing methodology such as this developed by Brown, et al., (2013) in which authors estimate the effects of extreme dry and wet events on macroeconomic indicators

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[2] gfdl-esm2m, hadgem2-es, ipsl-cm5a-lr, miroc-esm-chem, noresm1-m

using the Weighted Anomaly Standardized Precipitation index (WASP), by Burke et al., (2015) for the non-linear effects of temperature building on a quadratic function and finally the non-linear on bins approach is inspired by Schlenker & Roberts, (2009) in which exposure to different temperature levels is segmented to capture its non-linear effects on crop yields in the USA. The following table (Table 1) displays the outputs of the regression, climate data from the NCEP database are population density weighted using FAO data for year 2000, GDP per capita data are extracted from the World Development Indicators (World Bank, 2016), control variables and sources are described in the annex to this paper.

	Dependent variable: GDP per capita (log)	
	Current year	1-year lag
Precipitation		
Extreme/Severe dry	-0.0002*** (0.00004)	-0.0001*** (0.00004)
Moderately dry	-0.0001*** (0.00004)	-0.0002*** (0.00004)
Near normal dry	-0.0001*** (0.00003)	-0.0001*** (0.00003)
Normal dry	-0.00005** (0.00002)	-0.00003 (0.00002)
Normal wet	-0.00002 (0.00002)	-0.00002 (0.00002)
Near normal wet	-0.00004 (0.00003)	-0.00004 (0.00003)
Moderately wet	0.00002 (0.00004)	0.00004 (0.00005)
Extreme/very wet	-0.0002*** (0.0001)	-0.0002*** (0.0001)
Temperature		
Temperature	0.086*** (0.024)	0.076*** (0.024)
Squared temperature	-0.048** (0.023)	-0.040* (0.023)
Optimal deviation	*0.89*	*0.96*
Control variables		
Government expenditure	0.001 (0.001)	0.001 (0.001)
Governance	0.002* (0.001)	0.002* (0.001)
Gov. debt	-0.052*** (0.012)	-0.055*** (0.012)
ODA	-0.035 (0.066)	0.002 (0.067)
Remittances	-0.009*** (0.001)	-0.009*** (0.001)
Oil price	0.002*** (0.0002)	0.002*** (0.0002)
Constant	7.628*** (0.084)	7.619*** (0.082)
Observations	910	910
R2	0.978	0.978
Adjusted R2	0.977	0.977
Residual Std. Error (df=852)	0.142	0.142
F Statistic (df = 57; 852)	677.307***	675.216***

Table 1 Main regression results for precipitation (top-tier), temperature (middle-tier) and the control variables (bottom-tier). Authors' computation based on NCEP population-weighted precipitation and temperature data. The left-panel displays the results for the current year and the right panel for the 1-year lagged effects. The optimal temperature deviation is not an output of the regression but calculated by the authors from the results of the regression for temperature and squared temperature. Note: * significant at the 10 percent level; ** significant at the 5 percent level; * significant at the 1 percent level.**

For both current and 1-year lagged model results, both the effects of precipitation intensity and temperature is concave, indicating the possibility of an optimal level of precipitation and temperature above and below which the macroeconomic level performs less productively.

In the case of temperature, for the African countries, the mean deviation is about 0.89 degrees above the historical mean of the period 1950-1988 for the effects of temperature in the current year. For the one-year lagged consequences, the optimal temperature slightly rises at 0.96 above the historical mean but also becomes less significant than for the current year effect. This increment in optimal temperature between in the current year to the one-year lagged effect could indicate a possible rebound or recovery following a particularly warm year and its negative consequences on GDP per capita.

The effects of precipitation intensity follow a similar pattern with a possible optimal precipitation level being the “near normal wet” and the “moderately wet” categories of the SPI, indicating that African countries optimally perform economically when the level of precipitation is above the countries’ normal precipitation levels. This distance between the optimal precipitation level and the mean precipitation level of the countries could be interpreted as a possible adaptation deficit (Burton, 2004; Fankhauser & McDermott, 2014), or in other terms that African economies are not yet fully adapted to their current and mean precipitation climate. Depending on whether the mean precipitation climate will shift towards more dryness or more wetness as a consequence of climate change, the macroeconomic consequences of the long-term change in precipitation could either extend the distance to the optimal climate (dry trend) heightening these negative macroeconomic impacts or reduce the distance to the optimum and lessen the negative consequences – notwithstanding for the impacts of extreme wet and dry events. The following figure displays the results of the regression for the effects of precipitation intensity on GDP per capita.

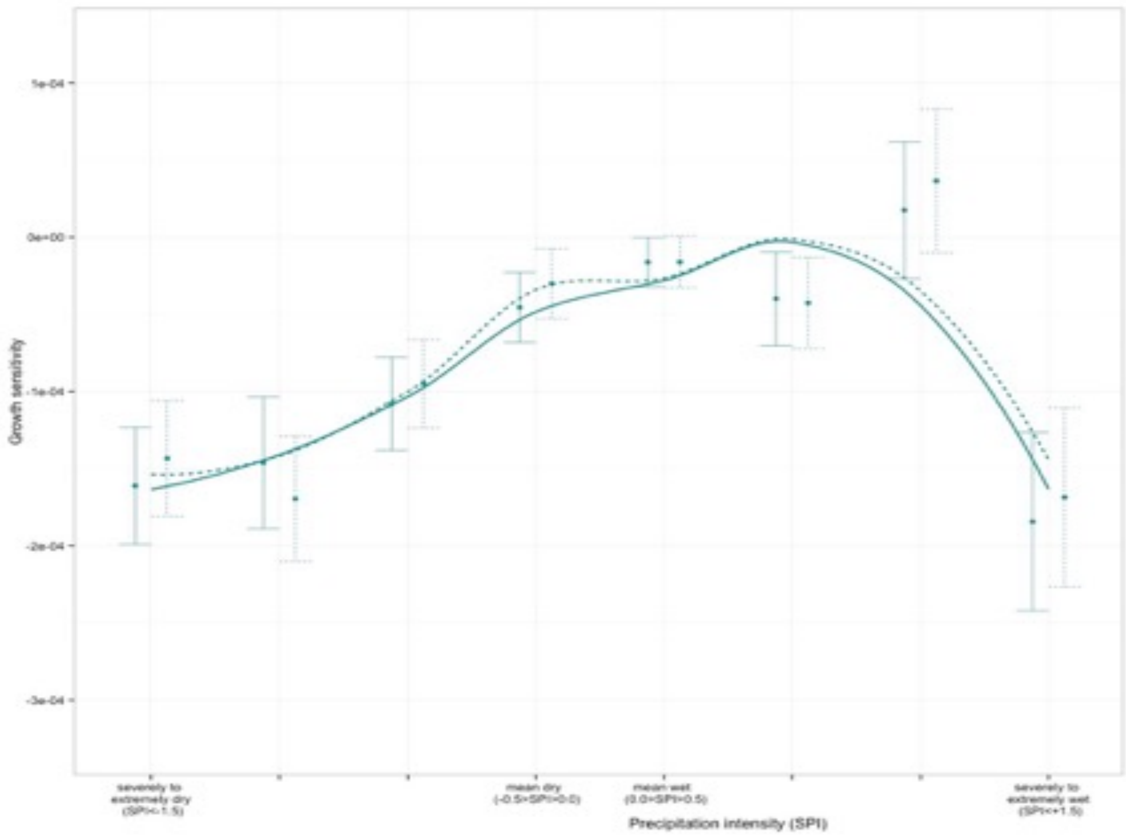

Figure 2 GDP per capita growth sensitivity to different level of precipitation intensity measured using SPI for the period 1980-2014 for Sub-Saharan African countries. The bold line presents the results for the current effects of precipitation intensity and the dashed line represent the one-year lagged effects. The error bars display the standard errors for each of the inferred coefficients in the regression. Authors’ computation based on Table 1.

The extreme of extreme / severe dry events and wet events display a similar negative sensitivity on GDP per capita. However, as extreme dry events are by definition slow-onset events, their effects of macroeconomic indicators have historically been more severe than extreme wet events. To some extent, the geographical footprint of droughts could also cover larger share of territory, but the analysis of the climate data projections in the first section of this study demonstrates that the difference in geographical footprint between extreme dry and wet events remains limited (Figure 1).

b. Future climate-induced economic risks

The sensitivity coefficients for temperature and precipitation are inferred at the country level using a randomization and filtering method based on Monte-Carlo simulation (method described in annex). The optimal coefficients are then used to estimate future climate-induced macroeconomic risk for each country in two different warming scenarios (RCP2.6, *low warming*; and RCP8.5, *high warming*). The GDP per capita growth risk estimated for the period 2010 to 2050 is adjusted around 2015 (2010-2020) to measure any further risks compared to current day climate and socioeconomic conditions of the countries. The risk accounts for the effects of precipitation and temperature. The following figure (Figure 3) displays the results of the GDP per capita risk forecast in the low and high warming scenarios for Sub-Saharan Africa.

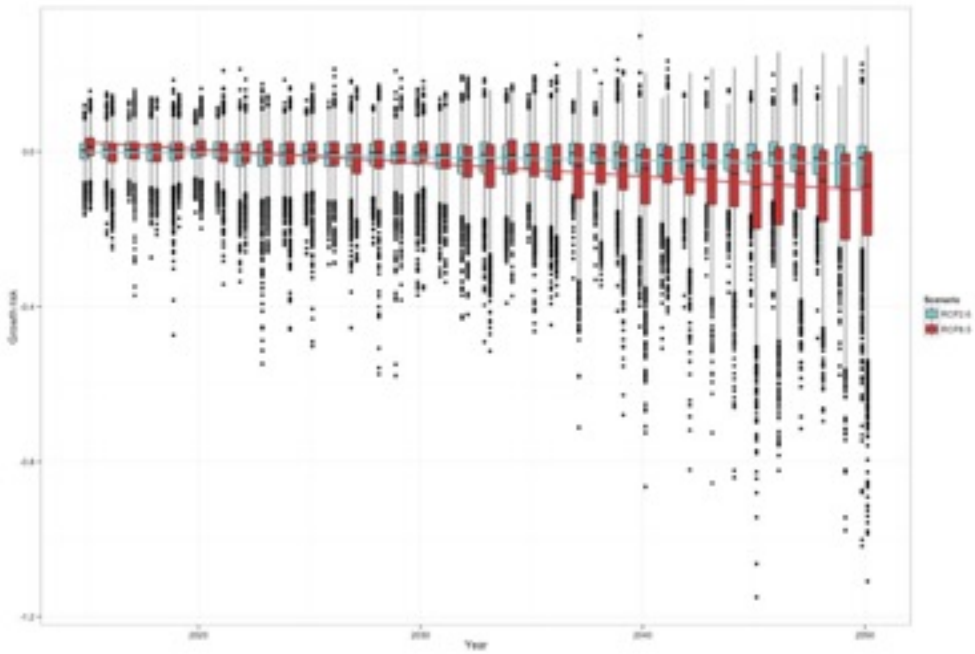

Figure 3 GDP per capita growth risk in Sub-Saharan Africa for the period 2015-2050 under a low (RCP2.6 in blue) and high warming (RCP8.5 in red) scenario. The box plots represent the 1^{st} to 3^{rd} interquartile range. The black dots represent are outliers, below the 5^{th} percentile and above the 95^{th} percentile of the distribution (or values above and below 1.5 times the 1^{st} to 3^{rd} interquartile range).

When accounting for both the impacts of precipitation and temperature on GDP per capita growth, it is observed that the macroeconomic consequences in the high warming scenario are almost twice as high as in the low warming scenario in the between 2040 and 2050 while being at a relatively similar level between 2015 and 2030. Following 2030, the deviation between both scenarios becomes more evident. Furthermore, in the high warming scenario, the interquartile range spreads larger than in the low warming scenario, showing a larger deviation to the mean macroeconomic effect possibly induced by a higher frequency of extreme negative values[3].

From 2015 to 2050, the share of the risk induced by precipitation in the overall macroeconomic risk decreases in both scenarios, with temperature progressively becoming the largest driver of the negative consequence on GDP per capita. In the period 2015-2030, temperature change explains 55 per cent of the overall climate-induced macroeconomic risk

[3] The regression coefficients of the 1^{st} to 5^{th} quantile regression in the high warming scenario are 2.5 to 2.9 times higher than in the low warming scenario showing a steeper increase in the frequency of very negative extreme events in this scenario.

in the high warming scenario and about 68 per cent in the low warming scenario. In the period 2035-2050, temperature explains about 80 per cent of the risk in the low warming scenario and about 95 per cent in the high warming scenario. Over the period 2015-2050, the effect of precipitation, including extreme wet and extreme dry events is overall constant. However, the frequency of precipitation extremes slowly increases in both scenarios. The large expansion of the effect of temperature on the overall macroeconomic risk originates, among other reasons, from the nature of the assumption used to measure the impacts of temperature on macroeconomic indicators. Indeed, with respect to temperature, once the optimal temperature deviation is reached (0.89 degrees above the historical mean for the Sub-Saharan African panel according to the regression results), further warming leads to rapidly increasing negative effects due to the quadratic form of the temperature damage function and the negative value taken by the squared temperature coefficient (here -0.048, statistically significant at the 5 per cent level). The quadratic form of the temperature damage function used in the regression model of this study is consistent with assumptions used in several publications, in which authors also assumed an optimal temperature above and below which the economies perform less productively (Burke et al., 2015; Fankhauser & Tol, 2005; Nordhaus & Boyer, 2003).

4. Discussions and conclusions

In the context of the Sustainable Development Agenda, the current analysis sheds additional light on the consequences of future climate change on the ability of African countries to reach the goal of decent work and economic growth. One of the key findings is that the role of precipitation, particularly precipitation extremes cannot be ignored when measuring the current and future effects of climate change on macroeconomic indicators. The model results described in this study show a decreasing influence of precipitation on macroeconomic risks. Even though the increasing losses incurred by temperature partially explains this increase, the climate models and data also play a significant role in this relative decrease. Indeed, the bias correction of the models used in this study seem to minimize the intensity of future precipitation extremes (Sippel et al., 2016). Furthermore, using regional climate models with higher geographical resolution could also contribute to improve the ability of economic models to account for the future risks induced by extreme wet and extreme dry precipitation events (McSweeney & Jones, 2016). A better integration of precipitation-induced macroeconomic risks is particularly important in the planning and decision-making processes on adaptation, where cost-benefits analyses are often used to determine the scale and adequacy of the investments. Omitting the negative consequences of precipitation change and extremes could lead undermine the macroeconomic case for investing in adaptation, more especially at the development planning level where long-term investment decisions are being made.

Additionally, future economic modelling of the impacts of climate change on macroeconomic indicators first need to better account for the impacts of precipitation, but also the progressive changing structure of the economies. In developing countries particularly, the structure of the economies is projected to experience significant changes – with a steep reduction of the contribution of the agricultural sector to GDP, predominantly compensated by a large growth of the industry and services sectors. The current study does not account for these changes. However, using the randomization-filtering method leads to inferring sensitivity coefficients, which optimally represent the countries' economic structure. Economic modeling, which integrates the results of structural change on the macroeconomic consequences of climate change shows an overall decrease of the countries' sensitivity to extreme dry events, but a progressive but slow increase of the sensitivity to extreme wet events – combined to an overall increase in the optimal temperature (Baarsch et al., *forthcoming*). In addition, the role of the overall development or income levels of the countries also need be better understood in order to further improve the modeling results. Planning adaptation and long-term investments in this support communities and economies cope with the adverse impacts of climate change requires an improved understanding of countries' future economic structure (Golub & Toman, 2016; Kocornik-Mina & Fankhauser, 2015).

Finally, the findings recall the importance of a global coordinated effort to mitigate greenhouse gas emissions in line with the 1.5ºC target of the Paris Agreement in order to maintain as low as possible the negative macroeconomic impacts of climate-related disasters and climate change throughout the first and second half of the 21st century. Overall, the current analysis shows that reaching the SDGs in developing and developed countries will necessitate coordinated action across and within developed and developing countries on mitigation as well as adaptation. As this study shows, unchecked warming levels, in line with current business-as-usual emissions, would lead to detrimental social and economic impacts, which could severely hamper the future capacity of developing countries to adapt and cope with the negative consequences of climate change. Developing countries' decreasing ability to adapt and cope would in consequence lead to a further increase in the losses and damages experienced by these countries, making the objective of a sustainably developed world without poverty totally out of reach.

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Annex: Methodological approach

This section describes the methodology used to assess socioeconomic risks and vulnerabilities at the sectoral and regional level in the five countries. It also explains the outputs to be expected from the methodology, as well as the potential gaps and limitations of the approach.

The historical analysis relies on a piecewise regression model, which aims at explaining GDP or sectoral value-added growth within bins of country exposure to precipitation intensity (using precipitation indices SPI, SPEI[4]), temperature and control variables, (such as oil prices, government spending, etc.) and country fixed effects. Panels are set up at the regional level (Coastal Western Africa, Sahel, etc.), for the following panel dimensions Countries x Years.

To estimate the effect of precipitation intensity and temperature change, the following panel regression model of the form is set up:

Equation 2

Where is the country time-invariant fixed effect, is a set of control variables and is the error term clustered at the country-level (time-variant factor). The model can also integrate time-lagged effects.

The dataset used is a pooled panel of countries presenting similar geographical and climatological characteristics, according to the Koppen-Geiger classification, for the period 1980 to 2014. For example, for African countries, pooling is based on the United Nations definition of African regions. However, owing to its distinguishable climatological characteristics an additional region, denominated Sahel, spanning from Senegal to Ethiopia is created. The Sahel region was created to better reflect the specific macroeconomic and climatological conditions of these countries.

The objectives of the regression model detailed above is twofold: 1- better estimating the historical sensitivity of countries' economy and therefore 2- providing a statistically significant set of sensitivity coefficients (elasticities), among other things to forecast future macroeconomic risks induced by climate change. However, inferred coefficients' standard errors become larger and larger as the precipitation index tends towards extreme values. In order to select the most appropriate sets of coefficients for the forecast, the following randomisation – filtering technique is applied, based on the out-of-sample methodology developed by Mark & Sul, (2012).

The regression (Equation 1) is performed for a given pool of countries. After verifying the condition that the inferred coefficients are independent in the covariance matrix, the coefficients are filtered following a data generating process using a Monte Carlo Simulation, such as:

Equation 3

In Equation 3, the mean value of the coefficients as well as their standard errors are used to produce a random set of coefficients within two standard error range distribution using a Monte Carlo Simulation. For each climate related parameters (precipitation intensity and temperature) as well as socioeconomic parameters (control variables), several thousands randomly defined coefficients are generated. Each set of coefficients is then used to calculate the dependant variable of interest using both climate and control variables, such as:

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[4] SPI: Standardized Precipitation Index (S. M. Vicente-Serrano & López-Moreno, 2005), SPEI: Standardized Precipitation-Evaporation Index (Sergio M. Vicente-Serrano, Beguería, & López-Moreno, 2010)

with: and

Equation 4

This approach sets control variables' coefficients for the region in line with the *ceteris paribus* assumption used for the forecast. The selection of forecast coefficients consists in choosing an ensemble of 10 sets for which the Root Mean Square Error (RMSE) between and is the smallest. Sets of the coefficients can be inferred at the regional or country level. In the current settings, for each country 10,000 draws were simulated.

The climate-economy coefficients (or sensitivities) obtained from the panel regression are filtered using a Monte Carlo-based randomisation-filtering method, which estimates the "optimal" sets of values for the coefficients at the country-level, whereby each of these sets allows the model to most closely reproduce observed climate-related fluctuations.

From the historical analysis, we infer the historical sensitivity of aggregate output Y_i, A_i, S_i and I_i to extreme dry (*d*), extreme wet (*w*) and extreme hot events (*h*). These coefficients are used are climate to economic outputs (value-added, GDP growth or GDP per capita) elasticities, based on the concept of climate analogues (Hallegatte, Hourcade, & Ambrosi, 2007).

For each sector and extreme type, the set of $\beta_{E,\ 1\text{->}m}$ coefficients is approximated, in the current model specifications *m*=8. The parameter $B_{stressors}$, inferred through equations 1, 2 and 3, denotes the ensemble of coefficients within $\beta_{E,\ 1\text{->}m}$, such as:

$B_d = [\beta_{E,\ 1} ; \beta_{E,\ m-2}]$

$B_w = [\beta_{E,\ 1+2} ; \beta_{E,\ m}]$

$B_h = \pi_E$

With B_d designating the ensemble of coefficients for projecting extreme dry events (droughts) economic consequences, B_w for the extreme wet events (possibly floods) and B_h the linear coefficient used as analogue for the effects of temperature. Each of these ensembles and coefficients are inferred at the sectoral and country levels, then denoted $B_{d,i,s}$ economic consequences, $B_{w,i,s}$ for the extreme wet events (possibly floods) and $B_{h,i}$.

Using the climate-economy elasticities for temperature and precipitation inferred in step 1, sectoral and aggregate risks for the 2030s and 2040s, measured in percentage point of GDP or value-added growth, are computed using projected exposure to the binned range of precipitation intensity and temperature deviations. Exposure is computed by applying the grid-level bias-corrected projections of five Global Circulation Models (gfdl-esm2m, hadgem2-es, ipsl-cm5a-lr, miroc-esm-chem, noresm1-m) from the Coupled Model Intercomparison Project Phase 5 - CMIP5 (Hempel et al. 2013). Therefore, for each *I* value five different values are being provided by the GCM ensemble. In addition to the sets of 10 optimal elasticities inferred by the Monte Carlo simulation, for every year and every scenario, 50 values of economic losses are being computed, providing a group of estimates relevant to an uncertainty assessment.

Future economic risk (R) is computed on a yearly basis, in a given sector s or at the aggregated level (Y) through the following equation, with in period 2010-2020:

Equation 5

Z in the total number of years . In Equation 5, the parameter for the period 2010-2020 measures the mean effects of current day climate-variability and climate change on macroeconomic risk (R). By subtracting the mean sectoral or aggregate risk in the period 2010-2020 the projections for the period 2015-2050 therefore only accounts for climate variability and climate change effects additional to current day conditions. R is here expressed in percentage points of sectoral value-added or aggregate growth.