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# What does Paris mean for Africa?
# An Integrated Assessment analysis of the effects of the Paris Agreement on African economies

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Abstract: Climate change is considered the biggest environmental challenge facing the world. The expected concomi-tant economic impacts of climate change are substantial, where the African continent is expected to be particularly vulnerable. Research is needed to support the development of sound climate policies in Africa. This paper develops a new Integrated Assessment Model -AD-AFRICA- which allows a comprehensive analysis of climate change impacts and adaptation in Africa. The AD-AFRICA model divides Africa into five regions and includes seven specific climate change impacts. The effects of the Paris agreement Intended Nationally Determined Contributions (INDCs) and the below 2 degrees target are investigated. The results show that though the INDCs reduce impacts, reaching the goal of the agreement will further reduce impacts by almost 1.6 % of GDP (588,731 US$ Billion). This highlights the importance of re-examining the level of INDCs. Furthermore, our results show that health and tourism impacts are highest and that different regions in Africa are more vulnerable to different climate change impacts depending on their level of development and regional characteristics. Finally, the withdrawal of the US from the Paris Agreement would result in an additional climate change burden of around 87 US$ Billions to Africa.

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# 1 INTRODUCTION

Climate change is considered to be the biggest environmental threat of our time (IPCC (2017)), the cause of which is anthropogenic greenhouse gas (GHG) emissions arising mainly from production [1], transport, heat and power, and animal agricultural practices. Greenhouse gasses accumulate in the atmosphere, which in turn leads to changes in the climatic system [2] (Solomon (2007)). Climate change is observed through the increasing mean surface and ocean temperatures, decreasing global ice sheets and increasing sea level rise [3] (IPCC - Pachauri et al. (2014)). These climatic changes result in impacts to societies and economies. Some examples of such impacts include; the destruction of marine ecosystems, extreme weather events, drought, flooding, forced migration, changes in crop yield and the frequent occurrence of heatwaves and extreme weather events. Furthermore, climate change is expected to bring an additional risk of food shortage, water scarcity and increased exposure to climate-related diseases such as malaria, dengue, and diarrhoea (Pachauri et al. (2014), Carabine et al. ((2015)), Schellnhuber et al. (2012), Clements ((2011))).

The potential climate impacts and severity thereof are expected to differ considerably across regions, countries and within societies where generally poorer populations are the most impacted. Though Africa as a region has contributed the least to global emissions over the past century (Niang et al. (2014),Carabine et al. ((2015)), IPCC (2017)), it faces the highest expected impacts [4].

For most African countries, climate change impacts present not only a challenge in the future but are already felt in the present. Even with the current level of climate change (less than 1 $^0$C increase in average global temperature), many African countries suffer significantly from climate-related impacts (O'reilly, Alin, Plisnier, Cohen, and McKee (2003), Hope Sr (2009), Carabine et al. ((2015)), Magrath (2008), Hemp (2009), Brouwer and Nhassengo (2006)). Moreover, Africa faces other substantial and long-standing challenges that amplify its vulnerability to climate change. These include; high dependence on climate-sensitive sectors; poor planning and settlement schemes; poor risk and disaster management systems; poor infrastructure and lack of adequate public health institutions (IPCC (2017).

Estimating the expected impacts of climate change for different African economies is hence of high importance. While the majority of the existing literature estimates the potential climate costs for Africa as a whole, several studies have attempted to estimate costs at a regional level. And those which do examine regional impacts focus mainly on agricultural impacts only (For example Stuch, Alcamo, and Schaldach (2020), Dinar, Hassan, Mendelsohn, and Benhin (2012), Schlenker and Lobell (2010), Adhikari, Nejadhashemi, and Woznicki (2015), Lam, Cheung, Swartz, and Sumaila (2012), Parkes, Sultan, and Ciais (2018)). Studies that provide comprehensive multiple impact estimates focus mostly on national or local

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[1] According to IPCC (Pachauri et al. (2014)) between 1970 and 2010, the release of $CO_2$ from industries and burning of fossil fuels alone accounted for more than 70% of total increase in GHG emissions.

[2] The atmospheric concentration of GHG increased from 280 ppm in pre-industrial era up to almost 400ppm by the end of 2015(NOAA ((accessed March 31, 2016)))

[3] AR5 reported 0.19 m of rising global mean sea level between 1901 and 2010

[4] Climate costs for Africa are expected to reach 10 to as high as 15 % of its GDP by 2100 for the worse case scenario Clements ((2011)), Baarsch et al. (2020)

levels such as SEI (2009) and Watkiss et al. (2011). These studies are considered to be beneficial in designing effective climate policies at the local level. But the frameworks used in such studies are too specific to draw any conclusions concerning impacts in the rest of Africa.

Generally, the literature concentrates on the damage costs, while studies looking at the potential adaptation costs for Africa are scarce. The few previous studies that provide comprehensive continent and impact specific assessment of adaptation costs (such as I. UNFCCC (2007), WB (2006), Oxfam (2007), UNDP (2007)) provide short term estimates. Though short-term estimates have their merits, climate change represents a long-term phenomenon, with exponentially increasing impacts. Climate change costs (damages and adaptation) over the long term can be estimated within the framework of Integrated Assessment Models (IAMs).

IAMs are applied models that extends the neo-classical growth framework to include climate change and its concomitant impacts. IAMs include a number of components that together describe how economic activities result in emissions, which in turn affect the climate system (modelled through geophysical equations) and how in turn economies are affected by climate change through damages. Prominent examples of IAMs are MERGE, FUND, RICE, AD-RICE, AD-DICE, AD-MERGE and AD-WITCH [6]. IAMs are often used in policy analysis, but also receive significant critique in the literature (e.g. Pindyck (2013)). This paper addresses some of the main critiques discussed in the literature regarding IAMs, namely the weak empirical base of impact modelling and the high level of aggregation in regions and impacts. Though IAMs have significant shortcomings, we believe they remain the most comprehensive frameworks available to examine the relationship between climate change and the economies on the long term.

Several studies have applied IAMs models to analyse the impacts of climate change for Africa (Schaeffer et al. ((2013)), Clements ((2011)), VividEconomics (2012)). Nevertheless, in these studies, African countries are represented at a highly aggregated level, where Africa is a single region [7]. A continent-wide assessment is crucial in understanding the aggregate effects of climate change in a broader sense. However, regions in Africa face different realities in terms of development, climate conditions, sectoral dependencies, adaptation and mitigation abilities [8](Chinowsky, Schweikert, Strzepek, Manahan, and Strzepek (2011)), therefore from a regional policy-making perspective continent-wide results may be of little use. Furthermore, the empirical base of these estimates is limited, where data is often extrapolated from outdated data from other continents.

The current study develops a new integrated assessment (IAM) model for Africa; AD-AFRICA that allows for a more disaggregated analysis of climate change impacts for African countries. In the AD-

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[6] see Nordhaus and Boyer (2000) (DICE / RICE), Manne, Mendelsohn, and Richels (1995) (MERGE), Anthoff and Tol (2010) (FUND), K. C. De Bruin, Dellink, and Tol (2009) ( AD-DICE), Bosetti, Massetti, and Tavoni (2007)(WITCH),Bahn, de Bruin, and Fertel (2019) (AD-MERGE)

[7] the FUND model has a less aggregated approach, which divides Africa into 2 regions: North and Sub Saharan Africa. The FUND model, however, does not explicitly include adaptation

[8] For instance, by 2009 more than 95 percent of total population in Tunisia had access to safe water whereas in Mali safe water was only accessible by less than 1 percent of its population ((AFDB ((accessed February 31, 2016)))

AFRICA model, Africa is divided into five regions; Western, Eastern, Northern, Central and Southern Africa. Although we do not estimate costs at the country level, countries are aggregated into regions based on similarities in climate change impacts capturing important regional characteristics. This is a vast improvement, where previous studies considered Africa as one region. AD-AFRICA includes seven impacts which are; health (mortality and morbidity); agriculture; roads; coastal; fisheries; water and tourism. The model is calibrated using updated and Africa based impact literature and data. The empirical basis of these impacts also pose a significant improvement compared to the current literature. The model allows investigation of the overall economic effect of these impacts at a regional level or aggregated to Africa as one block region.

The impacts that African economies will face will depend on the level of climate change and hence the level of global mitigation. Due to the global public good nature of climate change, there is a need to address climate change at a global level through combined mitigation efforts. Politically, the coordination of global efforts to combat climate change started in 1992 when the United Nations Framework Convention on Climate Change (UNFCCC) was established. The convention set up a basic framework and principles for preventing the dangerous anthropogenic interference with the climate system (Meakin (1992)). In 1995, members of UNFCCC formulated a governing board named the Conferences of the Parties (COP). The COP meet annually to evaluate the implementation of the convention and make crucial decisions concerning global climate change policies. For instance, during COP3, the first legally binding agreement, the Kyoto Protocol, was adopted. The Kyoto Protocol has been succeeded by the Paris Agreement, signed in 2015. This formulated a basis by which members of the convention voluntarily submit their national emission targets through Intended Nationally Determined Contributions (INDCs). The Paris agreement relies on the INDCs to meet the objective of article 2(a) of the agreement which states that;

> *Holding the increase in the global average temperature to well below 2 $^0$C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 $^0$C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change*

However, according to the literature (UNFCCC (2015), (UNEP ((2015)), Boyd, Turner, and Ward (2015), Reilly et al. (2015), CAT ((accessed 2016))) the joint emissions pathways proposed in the INDCs will not guarantee a global average temperature of below 2 $^0$C by 2100. Rather, the INDCs projections lead to a global increase in the average temperature of around 2.7 to 3 $^0$C by the end of the century. The difference between emissions that would result in the Paris 2 $^0$C goal and emissions that would result from the INDCs is referred to as the *emissions gap*.

This emissions gap creates extra climate change challenges that may jeopardise the process of poverty reduction and development in Africa. Therefore, it is imperative for African countries to gain insights into how their climate change costs are expected to differ under various global mitigation policies and communicate these costs during the COP as part of their negotiation process. In this regard, we investigate the impact of global mitigation efforts on potential climate change impacts for Africa. This is done by comparing economic costs of climate change between mitigation pathways corresponding to aggregate effect of INDCs and a below 2 $^0$C pathway corresponding to article 2(a) of the Paris agreement. Moreover, two more mitigation pathways are included in the analysis; a worst case scenario corresponding to above 4 $^0$C and the current policy reference scenario, which extrapolates current climate policies in place into the future. Specifically, in this paper we address the following research questions:

-How do the INDCs affect climate change impacts compared to current policies?

-How much additional impact reduction would be achieved by reaching the 2 $^0$C goal? -How does the US withdrawal from the Paris agreement affect impacts?

This paper is as follows; section 2 gives description of AD-AFRICA model including the calibration and data of sectoral impacts and adaptation. Section 3 presents the summary of key findings. Section 4 presents a sensitivity analysis and lastly, a brief discussion and conclusions are presented in section 5.

# 2 Methodology and data

## 2.1 Description of the AD-AFRICA model

This section presents a short description of the AD-AFRICA model, all model equations are presented in the Appendix. The AD-AFRICA model is an Integrated Assessment Model (IAM) for Africa, where economic production leads to GHG emissions, which in turn, together with exogenously given emissions from the rest of the world, result in climate change. Although climate change includes a multitude of phenomena such as higher variation in weather and increased extreme weather events, in this model, climate change is represented by changes in global atmospheric temperature and rise in sea level. Climate change creates gross damages to the economy. Gross damages can be reduced to residual damages through adaptation, which is explicitly represented in the model. The structure of this adaptation and damage module are based on the AD-DICE/AD-RICE model (K. C. De Bruin et al. (2009), K. De Bruin, Dellink, and Agrawala (2009)).

In the context of this study, temperature and sea level rise paths are given exogenously to allow for the investigation of the Paris Agreement. African mitigation is hence fixed at the relevant levels and its related costs are not included in this analysis. The model comprises of five regions, which together represent all African countries. The regions are as follows: Western, Eastern, Northern, Central and Southern Africa. The regional aggregation follows the African Development Banks classification of regions, where regions consist of relatively similar countries in terms of economy and climate impacts. Climate change impacts are modelled for seven impact types: Coastal, Health, Tourism, Fisheries, Agriculture, Roads and Water. We have chosen these impacts based on the extent of their overall impact and the availability of data.

AD-AFRICA is a forward-looking Ramsey economic growth model. The model horizon starts in 2010 and runs for 50 periods where each period is 5 years. Each region maximises its utility, where regional utility is a function of discounted regional per capita consumption. Utilty is discounted over time and over the level of consumption per capita, where utility is assumed to increase with consumption but at a decreasing rate. This means that richer generation's consumption creates less marginal utility than that of poorer generations. Consumption for each region is defined as GDP net of climate change damages and capital investments. Investment is equal to savings which is endogenously chosen through the optimisation in the model.

Production (GDP) is calculated using a Cobb-Douglas function of capital, labour and technological change (Total Factor Productivity –TFP). The model assumes that the labour supply grows with population. The capital stock increases with investment and decreases with depreciation at an annual rate of 10 percent as is standard in the literature. Data on initial levels of capital, labour and TFP are taken from (Feenstra, Inklaar, and Timmer ((accessed 2015))) while gross output is taken from (WDI ((accessed 2016))). Both Population and GDP are calibrated based on the Shared Socio-economic Pathways (SSP2), where GDP is taken from (Dellink, Chateau, Lanzi, and Magné (2015)) and population from Wittgenstein ((2015))). The model finds the optimal balance between capital investments, adaptation investments, adaptation costs and consumption for each region and there are no transfers between regions.

Concerning climate change impacts, initial damages before adaptation are referred to as gross damages and are estimated for each of the impacts and region. These gross damages are a function of either global average atmospheric temperature change footnote [9] Global temperature change is used here as opposed to regional as most impact assessment are based on global temperature change and not regional. or sea level rise. In the AD-AFRICA model, these damages can be reduced through the use of adaptation.

The AD-AFRICA model includes two forms of adaptation namely stock (proactive) and flow (reactive) adaptation. This distinction has been made to enable a more accurate description of the costs and benefits of different forms of adaptation and hence the total adaptation costs. Flow describes adaptation measures that can be taken in reaction to climate change or climate change stimuli. This form of adaptation comes at a relatively low cost and is generally undertaken by individuals. Stock on the other hand refers to adaptation measures that require investments long before the effects of climate change are felt. This form of adaptation usually requires large scale investments made by governments. Examples of the two forms of adaptations for different impacts are given in table 1 below. The damage and adaptation equations are given in the appendix.

| Impacts | Flow ( Reactive) | Stock (Proactive) |
|---|---|---|
| Agriculture | Introducing drought tolerant crops.<br>Changing planting dates. | Construction of dams for irrigation.<br>Research and development on new crops<br>Diversification to other source of income. |
| Fisheries | Small Scale fish farming | Seaweed farming as alternative livelihoods<br>Aquaculture |
| Water | Rainwater collection<br>Use of hand-dug reservoirs | Desalination of the sea water<br>Water recycling<br>Building dams |
| Coastal | Beach and wetland nourishment<br>Planting of vegetation trees such as shrubs and creepers | Building physical infrastructure i.e dikes |
| Health | Vaccination against cholera<br>Using insecticide-treated bed-nets; (reducing malaria exposure)<br>Eliminating breeding sites | Improved health care system<br>Warning systems e.g. for famine or extreme heat<br>Improvements in water supply and sanitation |
| Roads | General maintenance, i.e repairing cracks on paved roads or potholes on sand roads due to high temperatures and precipitation respectively | New construction upgrade that include change in design or material. i.e Upgrade from sand to paved roads or using asphalt mix design for paved roads |
| Tourism | Building of swimming pools<br>Air conditioned safari vehicles | Shifting to less-climate dependence tourism e.g culture and historical |

**Table 1: Examples of Flow ( Reactive) and Stock (Proactive) adaptation options.**

The impact and adaptation modules of AD-AFRICA is calibrated based on estimates of impacts; and adaptation costs and benefits from the impact literature. More precisely for each climate impact sector the damage costs, adaptation costs and adaptation benefits for each region were estimated based on available impact studies and expert judgment.The nest section describes this process in more detail.

## 2.2 Sectoral calibration and data

In this section, the various impacts included in the model are described. Further details and the equations are given in the appendix.

### 2.2.1 Agriculture

Agriculture is important in Africa, where it plays a central role in the livelihood of many people and has direct impacts on nutrition, hunger and poverty. A large percentage of the population in Africa, mainly in rural areas, still derive their entire livelihood from rain fed and small-scale subsistence agriculture activities (Clements ((2011))), where seemingly small economic impacts can be disastrous for many communities. Here we focus on the economic impacts on agricultural crops only and do not address any secondary impacts and impacts on other agricultural products are not included.

In the climate impact assessment literature, agriculture has received more attention than other impacts. The estimated impacts in the literature vary immensely where the outcomes depend on different assumptions such as inclusion and exclusion of the $CO_2$ fertilization effect. To mention a few examples of impact studies; Knox, Hess, Daccache, and Wheeler (2012), Ringler, Zhu, Cai, Koo, and Wang (2010), Tatsumi et al. (2011), and Fischer (2009). In the calibration of the agricultural impacts, we apply data from the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP), which gives estimated crop yield changes from various models of which we take the average.

The current study estimates the potential effect of climate change on agriculture sector for each region through its impact on the crop yields of maize, soy, wheat and rice. We calibrate a quadratic function to describe the relation between change in temperatures and crop yields. In the model we take carbon fertilization effects on crop yields into account and assume current irrigation levels continue. Up to a certain temperature, climate change increases the yields of some crops in some regions as the carbon fertilisation effect dominates.

We monetize the loss or gain per crop by firstly calculating initial production in current million US$ per crop (FAOSTAT ((accessed February 31, 2016))). Climate change induced yield changes are then translated into increased or decreased total crop production in monetary terms. The relative importance of the agricultural sector in production is expected to decrease as countries develop. This relation is estimated based on Tol (2002), where the share of agricultural production in GDP is assumed to decline with economic growth. Hence the importance of the agricultural sector is assumed to be inversely related to economic development and the magnitude of damages depends on the sector's share in the total output for each region.

### 2.2.2 Tourism

Most African economies depend heavily on weather related tourism such as wildlife safaris, beach holidays and other recreational activities. This type of tourism is vulnerable to climate change; as temperatures increase the amount of tourism days are expected to decrease for many African countries. Safaris are no longer attractive for tourists when it is severely hot or wet. Climate related Tourism impacts will depend on the effects of climate change on tourism days and on how much tourism contributes to GDP.

We simulate future impacts of climate change on tourism for each country in Africa using the same estimation technique as the Hamburg tourism model (Hamilton, Maddison, and Tol (2005)). The Hamburg model estimates arrivals of international tourists given average temperature, per capita income, coastline length and total area of the region. Here, we re-estimate the Hamburg model based on more recent data on African countries under with and without climate change scenarios. We estimate climate change impact on tourism by subtracting the number of estimated international arrivals given climate change from the estimated arrivals without climate change. We then multiply the difference by income per tourist to get the value of total tourism loss. Again, the share of tourism income in total income is assumed to fall with economic development (Tol (2002)). Data concerning land area, coastline length, tourism income and international tourism arrivals is collected from WDI ((accessed 2016)).

### 2.2.3 Fishery

Changes in the climate are projected to interfere with fishery ecosystems through coral reef bleaching, intrusion of saline water and high evaporation in catchment areas resulting in altered distribution and quantity of fish catch. Moreover, extreme events of flooding and large storms are expected to impose difficulties in fishing processes and damage fishing infrastructure (Lam et al. (2012)). Climate change impacts through fishery can be assessed through its indirect effects on food security, fish related jobs and industries. In this assessment we estimate the economic impact which is calculated by estimating the impact on the landed value of fisheries and multiplying this by the national fishing output multipliers. This captures, albeit in a static manner, the impact of fishery on other sectors of the economy.

We project climate impact on fisheries for West and Northern Africa only. As assessed by Cheung et al. (2010) future catch potential of fisheries at the coasts of these two regions are vulnerable to climate change, whereas impacts in other regions are expected to be negligible.

The current assessment uses underlying impacts from Lam et al. (2012). Lam et al. (2012) estimates the response of the fishery sector to climate change for Western Africa and the same impacts are extrapolated on Northern Africa, since impacts in Western and Northern Africa are expected to be similar (Cheung et al. (2010)). The benchmark impacts data from Lam et al. (2012) are then converted into percentage of GDP and a linear damage function is assumed to portray the relationship between fishery production and climate change. Gross damages are then calculated by multiplying these impacts by the gross fishery product function. We use initial fish production data from FAO ((accessed 2015)) to calculate the initial fishery product. As with agriculture and tourism impacts, we assume the share of fishery production in total production decreases as the economy grows.

### 2.2.4 Coastal

Thermal expansion and the melting of ice sheets due to the warming of the global climate are reported to be among the major factors contributing to rising global sea levels (Stocker et al. (2014)). Rising sea levels are projected to cause severe damages in the future. Examples of these damages include; displacement of people, flooding, altered water run-off, intrusion of saltwater, forced migration and even the loss of livelihood for societies living along the coastal area (Hinkel et al. (2012), Brown, Kebede, and Nicholls (2011)).

The current work relies on (Brown et al. (2011)) in the calibration of gross damage and adaptation costs for African countries due to rising sea levels. Brown et al. (2011) applies the DIVA model, which includes damages with and without adaptation for various sea level rise scenarios. The damages include costs of land loss, salinity intrusion, forced migration, people facing flooded and salinization costs. Adaptation costs include the construction of dikes and beach nourishment costs.

We calibrate the damage parameters by calculating regional costs as percent of GDP over time. In this study, impacts are evaluated by looking at the differences between costs in the sea level rise scenarios and the no sea level scenario such that investments needed given the current condition are excluded in the analysis, i.e. protection needed for current climatic conditions is not included in the calculation of adaptation costs. In calibrating the adaptation costs, we treat costs of seawall (dike) construction as a stock adaptation measure and beach nourishment as a flow adaptation measure.

### 2.2.5 Road infrastructure

Road infrastructure is considered to be an important component of a country's development process and economic growth. Unfortunately for African countries, road infrastructure is poorly developed despite being the main mode of transport (AFDB ((2014))). Consequently, the overall condition of road infrastructure in Africa in combination with a low adaptive capacity increases the vulnerability of the continent to the risks associated with climate change. High temperatures are noted to affect the hardness of road surfaces and expose it to cracking hence influencing the roadFLs lifespan (Galbraith, PRICE, and Shackman (2005), Chinowsky, Hayles, et al. (2011)).

Our calibration is based on the earlier work of Chinowsky, Schweikert, et al. (2011), which includes several steps to estimate the future impact of climate change stimuliFLs on road lifespan with and without adaptation. Adaptation includes the costs of constructing new road networks and repair costs. Chinowsky, Schweikert, et al. (2011) acknowledged the geographical and development differences within the continent and divided Africa into several regions. However, the aggregation approach used by Chinowsky, Schweikert, et al. (2011) does not correspond with the one used in the current assessment. We therefore approximate the presented costs for each country and re-aggregate these into the AD-AFRICA regions.

### 2.2.6 Water

Water shortages are for most African countries not a new phenomenon and climate change is expected to bring large increases in water demand in the continent (Clements ((2011))). The projected climate change impact on the potential supply of water is expected to vary between regions. Some regions such as Eastern Africa are expected to have increased water supply while Southern parts of Africa expect a decline in water supply (Kirshen (2007), Clements ((2011))).

Here we base our estimates on the potential damage and adaptation costs associated with water impacts for African regions using the earlier work of Kirshen (2007). Kirshen (2007) estimates the potential costs of adaptation to meet additional water demand due to climate change. These additional capital costs include; additional reservoir storage, additional wells, reclaimed wastewater and desalination. Operation and maintenance costs are not included in Kirshen (2007) but are partially accounting for due to the depreciation rate of capital in the AD-AFRICA model.

#### 2.2.7 Health: mortality and morbidity

The health systems in Africa remain inadequate, with both an insufficient number of facilities and poor quality of care despite the continent seeing some improvements over the past decades (AFDB ((2014))). Increasing temperatures and precipitation due to climate change are expected to pose large additional risks to human health in Africa (AR1-AR5 IPCC (2017) reports). The climate change impacts on crop yields and water scarcity increase the risk of food insecurity and reduce the accessibility to clean and safe drinking water. This is expected to increase the risk of diseases such as cholera, malnutrition and diarrhoea. In additional to that, high temperature is also expected to influence the life cycle of insects and also introduce vector borne diseases such as malaria to new places as well amplifying the diseases in the areas where it already exists (Githeko, Lindsay, Confalonieri, and Patz (2000)). Climate change induced floods also create perfect breeding grounds for insects.

The data used in the assessment of additional deaths due to climate change through malaria, diarrhoea, undernourishment and heat related mortality is taken from a previous impact study of WHO (2014). WHO (2014) projects an additional number of population at risk of losing life as a result of climate change for several emission scenarios. WHO (2014) estimates take into account the positive effect of social economic development on projections of mortality rates.

## 3 Results

This section presents the results of our analysis, focusing on damage and adaptation cost estimates. These results should be interpreted, keeping the assumptions of the methodology in mind. Firstly, we examine only a few of the numerous climate impacts and total impacts are likely to be larger. Secondly, the large amount of uncertainty surrounding any estimates over the long term should be recognised.

### 3.1 Mitigation scenarios

The level of future climate change and the resulting impacts will depend on the level of global mitigation efforts. In this regard, we explore four mitigation scenarios, namely; Representative Concentration Pathways (RCPs) 8.5 and 2.6, current policy reference (POLREF) and pledges under Intended Nationally Determined Contributions (INDC). RCP8.5 is a mitigation worst case scenario, where no mitigation policies take place and a low level of technological progress (and hence tehnological decarbonisation) is assumed. RCP2.6 refers to a scenario of high mitigation effort leading to below 2 degrees temperature increase corresponding with the Paris agreement goal. POLREF extrapolates current mitigation policies into the future. In the INDC scenario, the national mitigation pledges made under the Paris Agreement are assumed to be met. A description of these scenarios is given in table 2. The associated increases in temperatures and sea level rise over time are illustrated in figure 1.

| Mitigation scenario | Description | Temperature ($^0$C) | Sea level rise (meter) |
|---|---|---|---|
| RCP8.5 | Corresponds to over time increase in emissions due to the absence of mitigation policies, high population growth and slow income and technological growth (the worst case scenario). | Above 4 | 1.5 |
| POLREF | Reflects global mitigation policies that are currently in place and assumes no further mitigation efforts are taken. | 3.5 | 1.1 |
| INDC | This represents collective impact of the Paris agreement emission pledges submitted by parties to the convection under UNFCCC. | 3 | 0.9 |
| RCP2.6 | This represents a mitigation pathway consistence with the aim of achieving the main objective of the Paris agreement. | Below 2 | 0.5 |

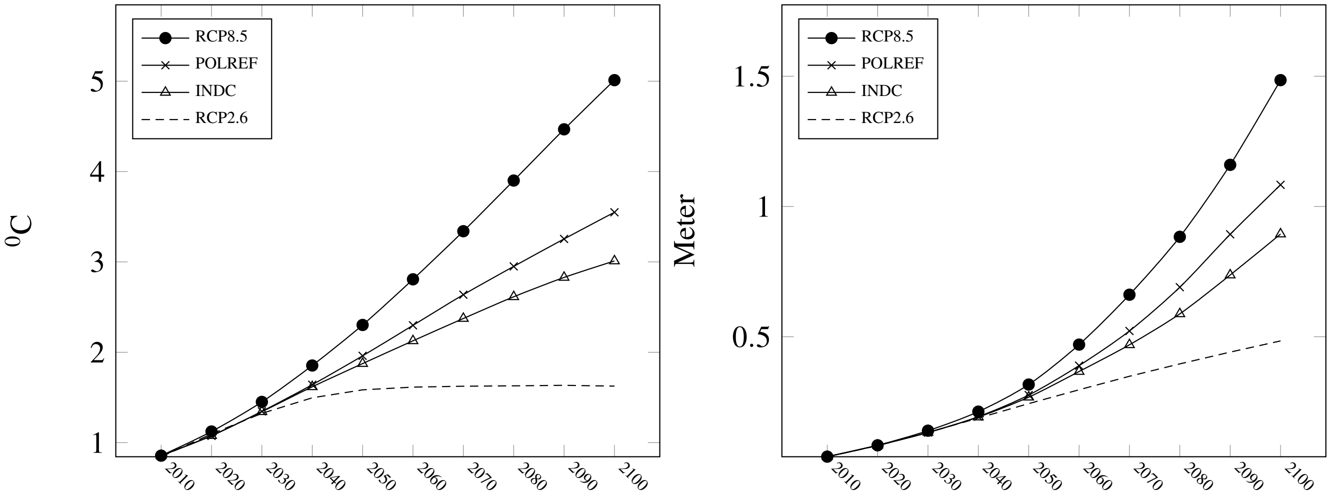
**Table 2: Projections of increase in the global average temperature and sea level rise above pre-industrial levels by 2100 under four mitigation scenarios**

### 3.2 Continent wide impacts

In this section, we examine the aggregate results for the continent Africa as a whole under the mitigation scenarios discussed above. We will discuss the results concerning gross damages (GD), residual damages (RD) and adaptation costs (PC).

Figure 2 presents gross and residual damages for 2050 and 2100 in terms of percentage of GDP and figure 3 shows gross damages in US $ Billion over time. As would be expected we see less gross damages when mitigation policies are more stringent. In the RCP8.5 scenario, e.g., total gross damages are estimated at 2.8% of GDP ( 2923,632 US $ Billion) in 2100, the corresponding damages for the RCP2.6 scenario are 0.6% of GDP (637,302 US $ Billion) in 2100. Further, the differences in damages between the scenarios are shown to increase with time, where the differences are more pronounced in 2100 compared to 2050 (shown in Figure 2). For instance the difference between RCP8.5 and RCP2.6 is 0.5% of GDP in 2050, but increases to 2.2% in 2100.

In terms of percentage of GDP, the RCP8.5 and POLREF scenarios show increases in gross damages between 2050 and 2100. This would be expected, given that temperature change increases over time. However, both the INDC and RCP2.6 scenarios show less gross damages in 2100 than in 2050 in terms of percentage of GDP. There are several mechanisms driving this result. Firstly, African economies are expected to undergo considerable economic growth over the next century, as such increases in GDP will



**(a) Temperature** **(b) Sea Level Rise**

**Figure 1: Projections of average Global Temperature and global sea level rise above pre-industrial levels by 2100.**

deflate the gross damages expressed as a percentage of GDP. Secondly, as African economies develop over time, certain climate change impacts such as health, agriculture and tourism decline. This is due to the lower economic dependence on tourism and agriculture and the increase in health infrastructure. In these scenarios mitigation levels are high enough such that the impact reduction due to economic development outweighs the impact increase due to a higher temperature.

In terms of US$ billion, as shown in figure 3, gross damages increase over time for all scenarios. Furthermore, these damages differ substantially across scenarios, where again the differences becomes more pronounced over time.

Gross damages are reduced through adaptation in the model and when applied optimally Africa would bear the cost of residual damages and adaptation costs. Adaptation is needed even when the world adopts the most ambitious global mitigation policy, however adaptation policies alone cannot liberate Africa from climate change damages. The differences between gross damages and residual damages indicate the adaptation potential of reducing climate change impacts. As Figure 2 indicates, adaptation can be a powerful policy tool to reduce impacts. When examining residual damages, only the RCP2.6 scenarios shows a decrease in residual damages from 2050 to 2100, where the damages are around 0.8% of GDP in 2050 decreasing to 0.5% by 2100. In contrast, residual damages for the other scenarios increase over time.

Adaptation to climate change is crucial but it comes at a cost, Figure 4 shows total adaptation costs under the four scenarios for 2050 and 2100. Note that, the presented costs combine both investments in proactive adaptation (SAD) and reactive adaptation expenditures (FAD).

It is clear from figure 4 that adaptation costs vary considerably across mitigation scenarios. The more stringent the mitigation scenario, the lower the adaptation expenditure. This is to be expected as

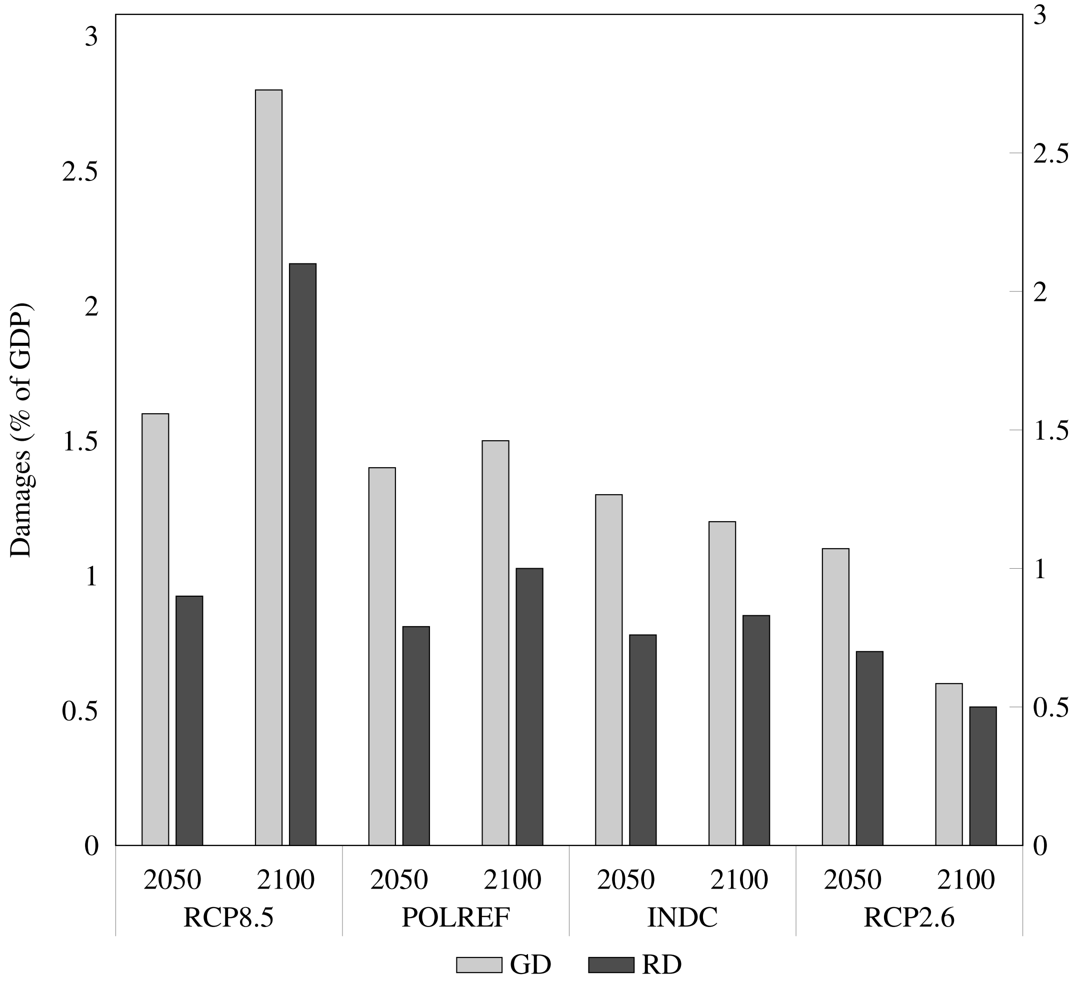


**Figure 2: Projections of total gross (GD) and residual damages (RD) as % of African GDP for 2050 and 2100.**

adaptation and mitigation are substitutes for each other and confirms the importance of simultaneously considering and coordinating adaptation and mitigation policies.

Concerning the distribution of total adaptation costs over time, the costs are higher in 2050 than in 2100 for the POLREF, INDC and RCP2.6 scenarios (Figure 4). This can be explained by the time composition of the different adaptation options (proactive and reactive). Accordingly, the model finds the largest share of total adaptation for most scenarios in 2050 to be made up by proactive measures. Proactive adaptation measures require long-term investment which ensure protection in later years. Thus, the high total adaptation costs in 2050 reflects the build-up of proactive adaptation capital. In RCP8.5, investment costs in proactive adaptation are high and dominate total adaptation costs throughout the model horizon. This can be explained by the high gross damages, which warrant proactive adaptation measures throughout.

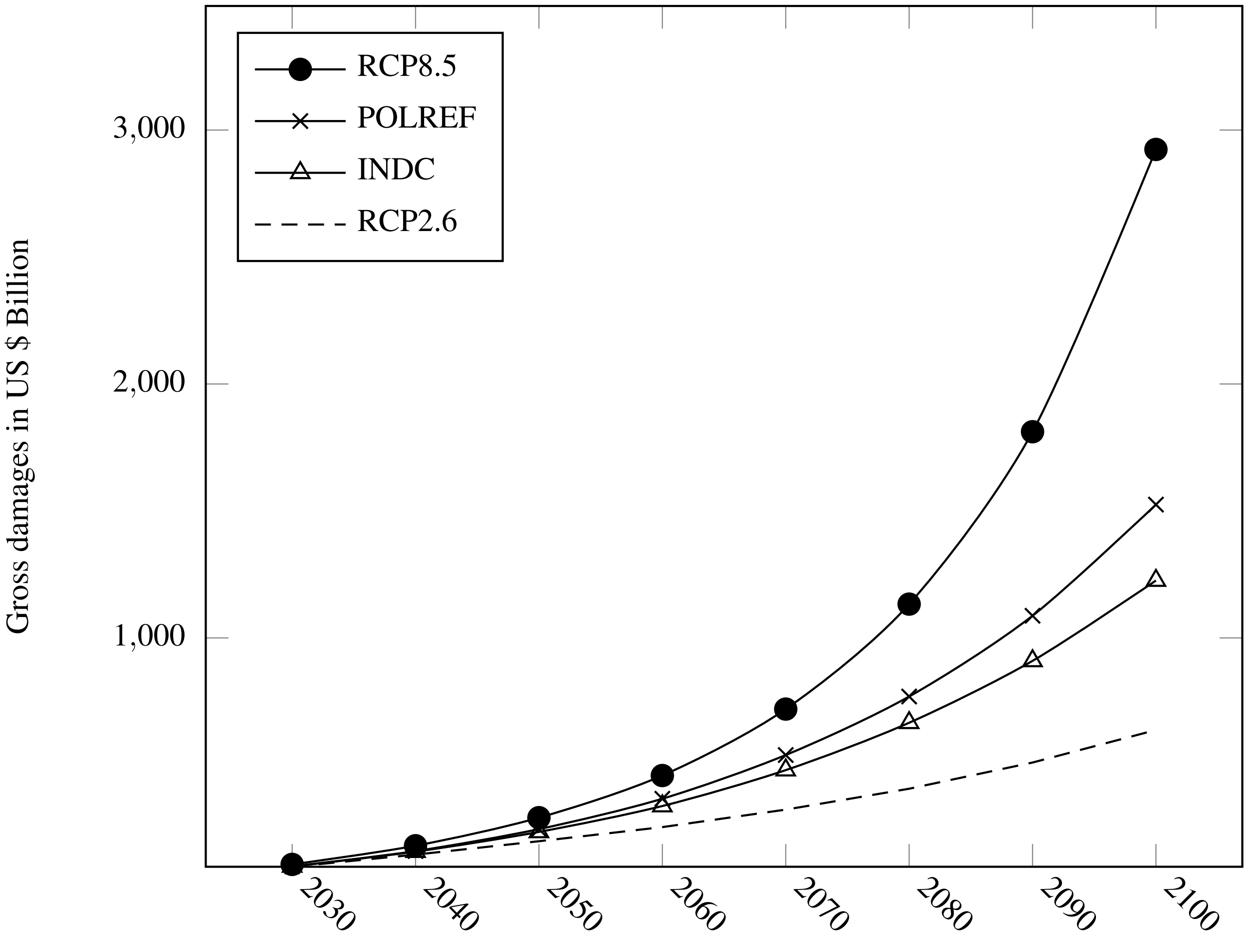


**Figure 3: Over time projections of gross damages under different mitigation scenarios in US $ Billion.**

Focusing on the Paris agreement we see that the impacts of the agreement as it currently stands in terms of gross damages is a 0.3% of GDP decrease in 2100 which is approximately 300 US $ Billion. This represents the difference between the POLREF and the INDC scenarios. In terms of residual damages and adaptation costs, the impact is about 0.2% and 0.02 % of GDP (approximately 194 and 19 US $ Billion) respectively.

Comparing the INDC, i.e. the Paris agreement commitments with the RCP2.6, i.e. the Paris agreement goal, we see alarmingly large impacts. Gross damages are increased by 92 % in the INDC scenario compared to RCP2.6, residual damages by 43 % and adaptation cost by more than 100 %. In other words in term of impacts the current Paris agreement commitments fall far short of their goal. Indeed gross damage reduction is more than 200 % higher between the current commitments and the goal than between the policy reference and the commitments. In other words compared to current policies, the INDC bring

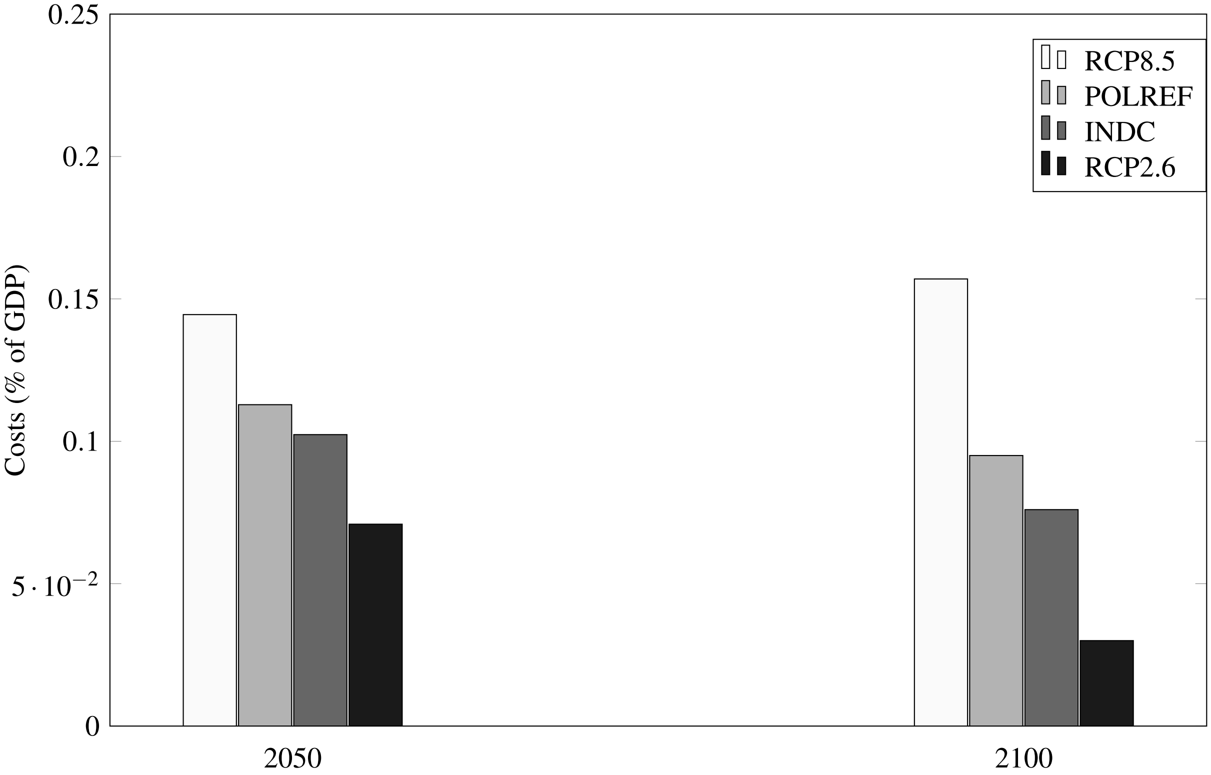


**Figure 4: Total adaptation costs as percentage of African GDP.**

us only one third of the way to the damage reduction of the Paris goal. This highlights the large impacts associated with the emissions gap and the need for future COP negotiations to address this issue.

## 3.3 Impacts across sectors

In this section we present results focusing on the impact sectors and regional differences. The results are only presented for a one scenario, namely the INDC scenario. This scenario was chosen as this is the projected outcome of Paris climate change agreement as it stands now.

Figure 5 compares the gross damages associated with the different climate change impacts over time. The results show large disparities in damages between sectors, where the largest impacts up to mid 2090s come from the health sector (mortality). However, the health impacts (mortality and morbidity) tend to decline over time. For example, mortality damages decrease from about 1% of Africa's GDP in 2030 to around 0.7% at the mid-century and drop even further to 0.3% in 2100. This is due to the high sensitivity of health impacts to economic development. The assumption here is that economic growth brings better health infrastructure, access to medical care, clean water and improved sanitation alongside effective treatment of diseases which becomes affordable as income rises.

The second largest sector in terms of impacts is the tourism sector. As shown in figure 5, gross damages in the tourism sector increase relatively steeply as temperatures increase, where damages in

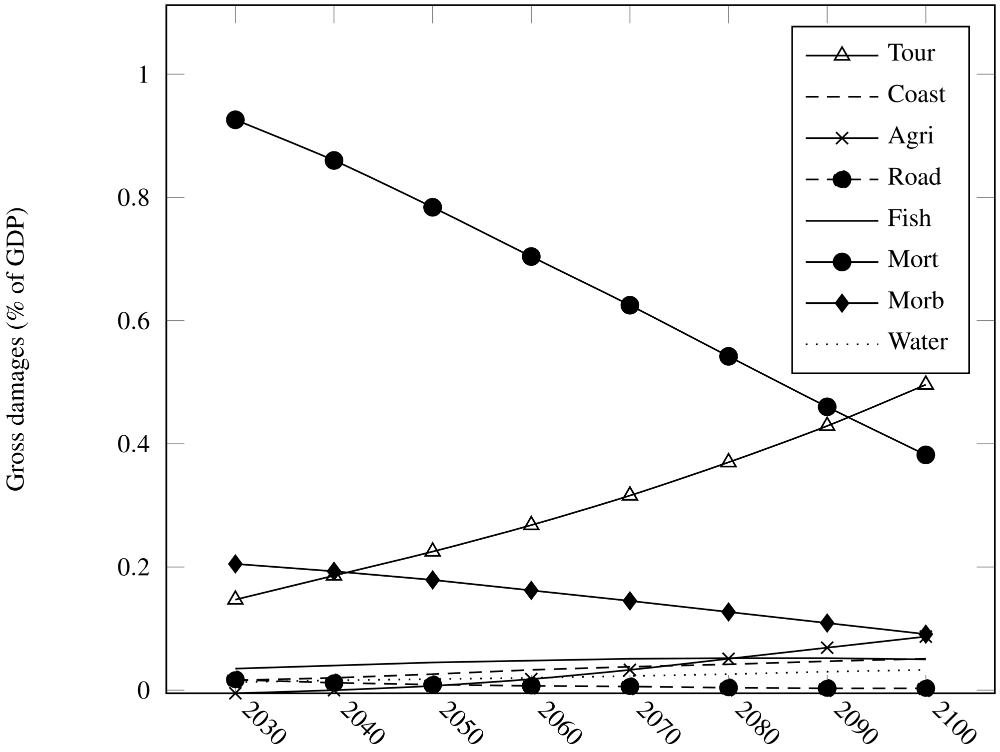


**Figure 5: Gross damages per impact sector as percentage of African GDP for the INDC mitigation scenario, i.e. under the Paris agreement.**

2100 are double those in 2050. Although for tourism we assume a reduction in vulnerability to climate change as economies develop, the increase in damages due to climate change completely overshadow that benefit.

The agricultural impacts are initially positive in all regions up to around 2030 and thereafter are negative and increasing throughout. The positive impacts at lower temperature are explained by the carbon fertilization effect on agricultural crops incorporated in the agricultural impact calibration. As pointed out by Baker and Boote (1996), the positive effect of increased atmospheric $CO_2$ concentration on plant growth through photosynthesis is high at least up to a particular temperatures above which it drops. Note that the results change considerably if carbon fertilization effect is excluded in the calibration of the sector, see section 4.4 for a sensitivity analysis regarding this.

For, water, coastal, fisheries and road, climate damages are comparatively small (figure 5). Water, coastal and fisheries impacts increase over time whereas for the road sector impacts decrease over time. In terms of the magnitude, the road sector has the smallest impact, approximately 0.003 % of African GDP by 2100. Note that this assessment does not include climate induced extreme weather events such as flooding and prolonged heavy rainfall in the calibration of impacts. Extreme weather events are considered to have relatively large impacts on unpaved type of road network (Chinowsky, Schweikert, et al. (2011)), which dominate the road infrastructure in Africa.

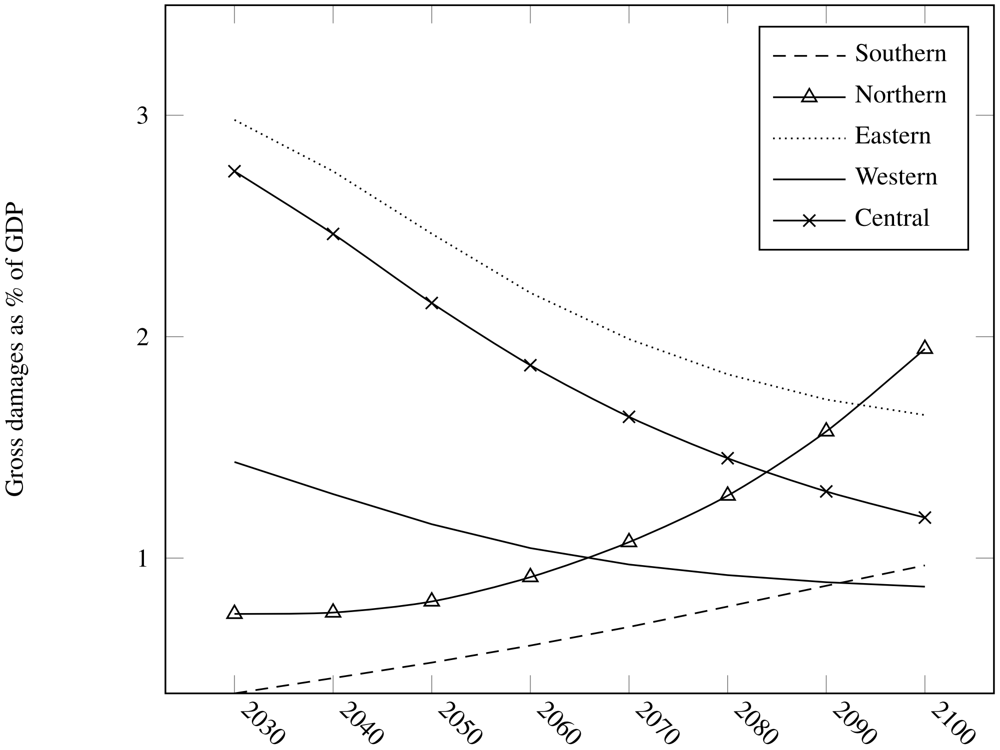


**Figure 6: Per regional total gross damages as percentage of regional GDP for INDC mitigation scenario.**

### 3.4 Impacts across regions

Shifting to impacts across regions (figure 6), we see that the Southern and Northern regions show increases in climate damages over time as percentage of regional GDP. On the other hand, Eastern, Western and Central Africa, show relatively high damages at the beginning of the century, which decrease throughout the century. These results are influenced by the rate of economic growth across regions where Southern and Northern regions are relatively rich and expected to have lower levels of GDP growth in the future. This comparatively increases the impacts in GDP terms.

On the contrary, the damages in US$ Billion displayed on figure 7 show that Eastern and Western Africa are expected to bear the largest burden from climate change by 2100 while the Southern region has the lowest damages. Comparing gross and residual damages in figure 7, we see that Northern region shows a high adaptation potential of reducing initial climate change damages (gross damages) i.e adaptation is projected to reduce about 63% of gross damages. This could be due to the high share of coastal impacts in total impacts in Northern Africa, where the potential to adapt to coastal impacts is extremely high. While for the Southern, Eastern, Western and Central Africa, the percentage of damages that can be reduced by adaptation are 52%, 27%, 26% and 28% respectively.

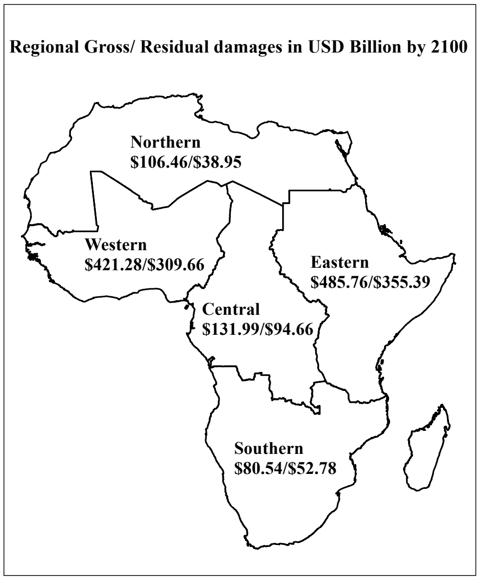


**Figure 7: The estimates of regional gross and residual damages in US $ billion by 2100.**

Table 3 presents the composition of gross damages between sectors in each region. Considering first the Southern region, the tourism sector composes the largest share of total damages in the mid to end of the century (above 60% of total in 2100). This reflects the relative importance of the tourism sector for the economy of Southern Africa. Also, Southern Africa is shown to be less vulnerable to climate change-induced health and agriculture impacts which is presumably the result of the relatively high level of development in the region.

In 2050, the highest share of damages for Northern Africa are from mortality and tourism impacts. By 2100, however, as mentioned above, coastal impacts dominate, comprising 40 % of the total regional damages (table 3). Besides, road impacts are also comparatively high in the Northern region. The relatively high damages to road infrastructure can be as a result of a large share of paved road in the total road network in the Northern region, where paved roads are highly affected by high temperatures (Chinowsky, Hayles, et al. (2011)).

Particularly, the health sector (mortality and morbidity) impacts are large in Eastern, Western, and Central Africa in 2100. Health impacts constitute approximately 60%, 40% and 39% of total gross damages of Central, Eastern, and Western Africa respectively. The prominence of health impacts explains the declining pattern of total gross damages over time for Eastern, Western and Central Africa in figure 6. Damages from other impacts such as tourism and water for Eastern; and fish for the Western region are also comparatively high (table 3). Nonetheless, increase in damages for these sectors are offset by the decrease in damages in the health sector, resulting in the downward trend of gross damages over time.

| | | | 2050 | | |
|---|---|---|---|---|---|
| | **Southern** | **Northern** | **Eastern** | **Western** | **Central** |
| Tourism | 0.365 | 0.206 | 0.339 | 0.140 | 0.143 |
| Coast | 0.007 | 0.077 | 0.004 | 0.005 | 0.039 |
| Mortality | 0.107 | 0.463 | 1.560 | 0.701 | 1.591 |
| Morbidity | 0.016 | 0.029 | 0.494 | 0.151 | 0.351 |
| Fish | | 0.035 | | 0.104 | |
| Water | 0.022 | 0.007 | 0.044 | 0.012 | 0.013 |
| Road | 0.010 | 0.009 | 0.010 | 0.008 | 0.011 |
| Agriculture | 0.001 | -0.022 | 0.014 | 0.03 | 0.004 |
| | | | **2100** | | |
| | **Southern** | **Northern** | **Eastern** | **Western** | **Central** |
| Tourism | 0.683 | 0.333 | 0.816 | 0.310 | 0.334 |
| Coast | 0.027 | 0.797 | 0.004 | 0.006 | 0.028 |
| Mortality | 0.077 | 0.674 | 0.501 | 0.280 | 0.596 |
| Morbidity | 0.012 | 0.042 | 0.159 | 0.060 | 0.132 |
| Fish | | 0.054 | | 0.100 | |
| Water | 0.027 | 0.008 | 0.071 | 0.017 | 0.018 |
| Road | 0.005 | 0.013 | 0.002 | 0.002 | 0.003 |
| Agriculture | 0.058 | 0.025 | 0.093 | 0.098 | 0.072 |

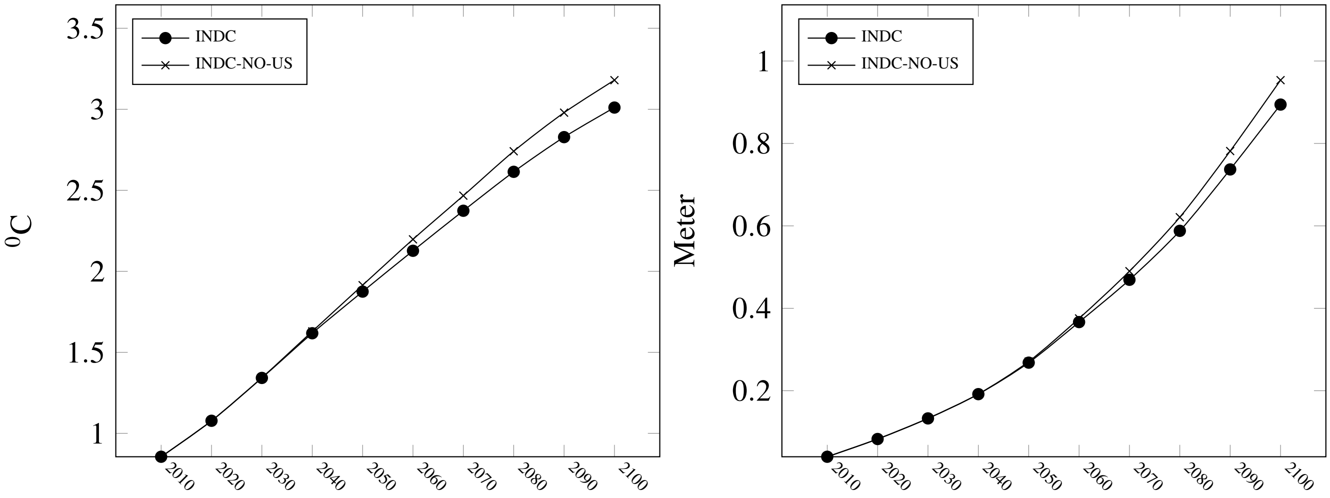
**Table 3: Projections of per sector regional gross damages as % of GDP in INDC scenario in the year 2050 and 2100**

### 3.5 US Withdrawal from the Paris agreement

The cumulative emissions of the US since 1900 significantly outweigh those of any other country. Today the US remains the largest per capita emitter country and the second-largest total emitter of $CO_2$ emissions (statistica ((accessed March 1, 2018))). By 2016, the US alone contributed to about 16 percent of the total global $CO_2$ emissions. Despite being the country that has contributed the most to climate change, the US announced its plans to withdraw from the Paris Agreement in June 2017. If the withdrawal is realised, difficulties and or delays in achieving the main goal of the Paris agreement are foreseen (Sanderson and Knutti (2016), Zhang, Dai, Lai, and Wang (2017)). Given the recent election results in the US, there is some hope that this decision to leave will be reversed. Figure 8 shows estimated temperature change and sea-level rise in scenarios with (INDC) and without the US pledge (INDC-NO-US).

From the figures, we see the US withdrawals result in higher temperatures and sea level rise. The difference is expected to be around $0.1^0$ C and 0.06 m in 2100 in temperatures and sea level rise respectively.

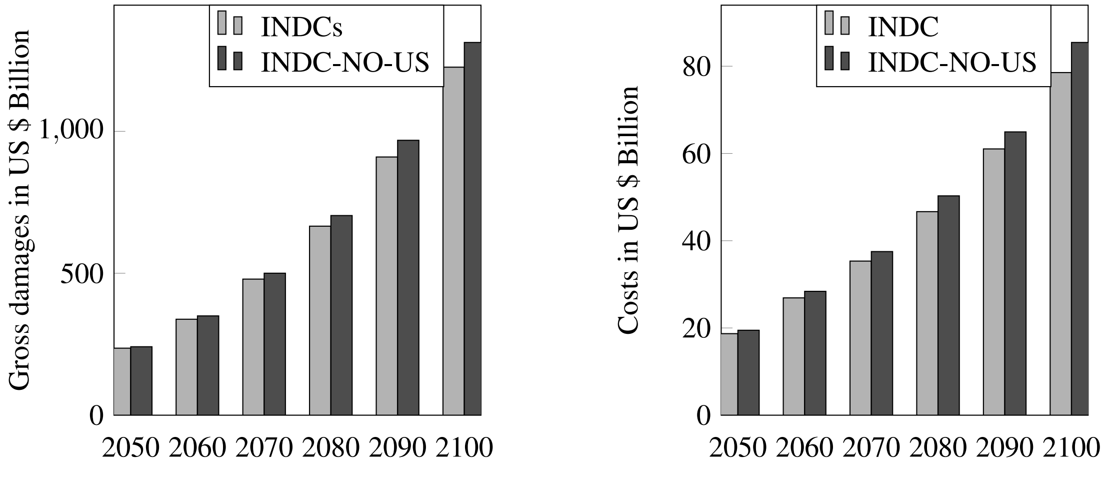
The associated gross damages and adaptation costs in terms of US $ Billion are shown in figures 9a and 9b. The possible repercussion resulting from the diverging interest of the US from the Paris agreement is more pronounced after the mid-century. As expected the US withdrawal is estimated to widen the gap between the main goal of Paris agreement and pledges from INDC even further. Our results show that



**(a) Temperature.** **(b) Sea Level Rise**

**Figure 8: Projections of average global temperature and global sea level rise above pre-industrial for the INDC with and without US.**

INDC without the US results in an additional 87 US $ Billions gross damages by 2100 compared to INDC with US. Moreover, Africa would need to finance an additional 7 US $ Billion in 2100 on adaptation costs if US deviates from the Paris agreement. These results confirm the important role the US has to play in any global mitigation agreement. And highlights the extend of the additional costs less developed regions face as a result of the negligent US international policies.



**(a) Total Gross Damages in US $ Billion.** **(b) Total Adaptation costs in US $ Billion.**

# 4 Sensitivity analysis

In this section, we investigate the sensitivity of our results to the assumption of the Carbon Fertilisation Effect and to the parameterisation of the regional output functions.

## 4.1 Exclusion of the carbon fertilization effect

To gain more insight into the climate change impacts on the agriculture sector, in this section we investigate the impacts of assuming no Carbon Fertilization Effect (CFE). Figure 10 illustrates the long term trends of gross damages for the agriculture sector with and without CFE under the INDC and RCP8.5 scenarios.

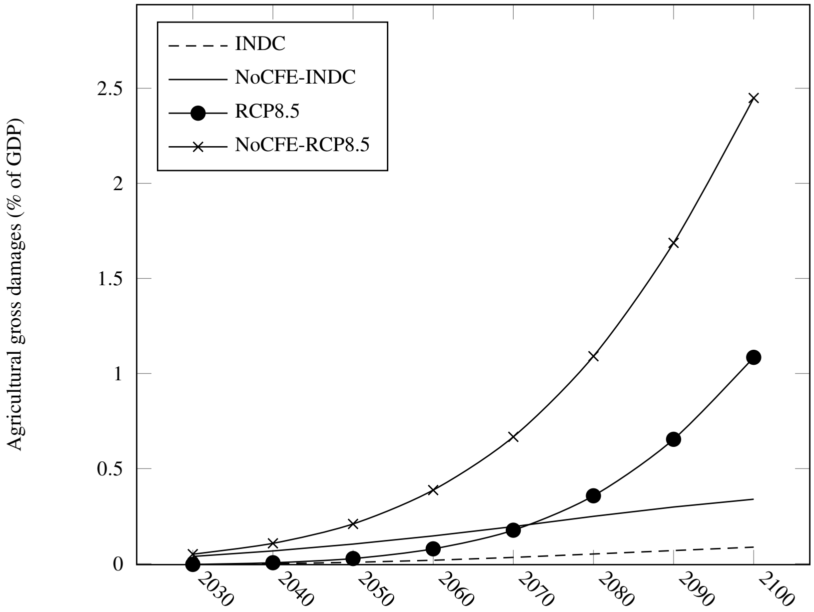


**Figure 10: Projections of gross damages for the agriculture impact sector given as percentage of Africa GDP for INDC and RCP8.5 scenarios with and without Carbon Fertilization Effect**

In the figure, a large difference is seen between impacts with and without CFE, where impacts are larger when CFE is not included. We assume that, agricultural impacts are reduced over time as regions develop and their dependence on agriculture decreases. However, as temperatures rise the influence of the non-linearity of the agricultural impact function increases. In the RCP8.5 scenario, which has high levels of temperature change, agricultural impacts increase significantly, specifically without CFE. Agricultural impacts without CFE are by far the largest of all impact sectors with gross damages of 2.4 % of GDP under the RCP8.5 scenario in 2100. These results indicate that the assumptions concerning CFE are a considerable driving force behind agricultural impact estimates. The uncertainty surrounding the impacts of CFE should be considered when interpreting agricultural estimates.

## 4.2 Economic growth

Nordhaus (2014) emphasizes the significant role that the choice of Total Factor Productivity (TFP) level plays in the long term growth of output as such, it is among the most important parameters in the calibration process. It is of exceptional importance when looking at regions such as Africa, where high levels of economic growth are assumed in the future. In essence, we examine what the impact is of over- or underestimating economic growth in Africa on our results concerning climate change impacts. We run the model with three different growth rates of TFP, a base case, a high and a low case. We decrease (in the low case) and increase (in the high case) the growth rate by one standard deviation. We follow Nordhaus (2014) and assume a standard deviation of just under half the mean value. Table 4 displays the corresponding average regional growth rate of GDP for each growth rate of TFP. Figure 11 shows output projections in US $ Billion for each growth rate of TFP for Africa as whole, where the corresponding damages are shown in figure 12 in GDP terms.

| Region | Low | Base | High |
|---|---|---|---|
| Southern | 0.102 | 0.150 | 0.203 |
| Northern | 0.071 | 0.102 | 0.137 |
| Eastern | 0.179 | 0.279 | 0.394 |
| Western | 0.187 | 0.283 | 0.393 |
| Central | 0.172 | 0.265 | 0.373 |

**Table 4: Projections of per regional average GDP growth rate over the century to growth rate of Total Factor Productivity.**

Table 4 show a slightly higher increase of average GDP growth rate from the base to higher growth rate of TFP than a reduction from base to low growth rate of TFP for all regions. Examining aggregate output trends over time as displayed in figure 11, we find output to be more impacted by higher growth rate of TFP compared to lower rate. GDP increases by more than 300 % from the base to high case, while the reduction from base to low case is only about 67% by 2100. Further, as emphasised in earlier studies (*see Solow (1956)*), we find the effect of model induced variations in TFP growth rate on output to be more prevailing in the long-run compared to the short-run. For instance, the variation of TFP growth rate from base to high show an increase of output by about 79 % in 2050 compared to more than 300 % in 2100.

Figure 12 shows that a lower economic growth rate leads to higher damages, i.e. about 2% in GDP which is approximately 615,7 US $ Billions in 2100. Though a higher rate of TFP has larger impacts on GDP, the effect of a high TFP growth rate in reducing climate change damages is minimal compared to the effect of low TFP growth rate on increasing the damages. For instance, in 2100, 0.9 % of GDP gross damages increased from income growth reduction from base to lower levels compared to a reduction of 0.2% of GDP from a shift from base to high levels.

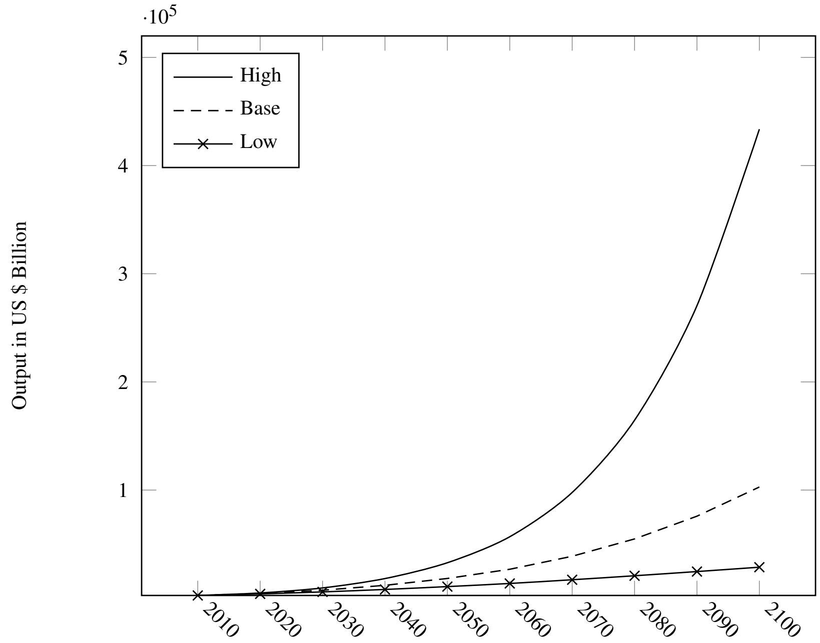


**Figure 11: Output in US $ Billion to growth rate of Total Factor Productivity**

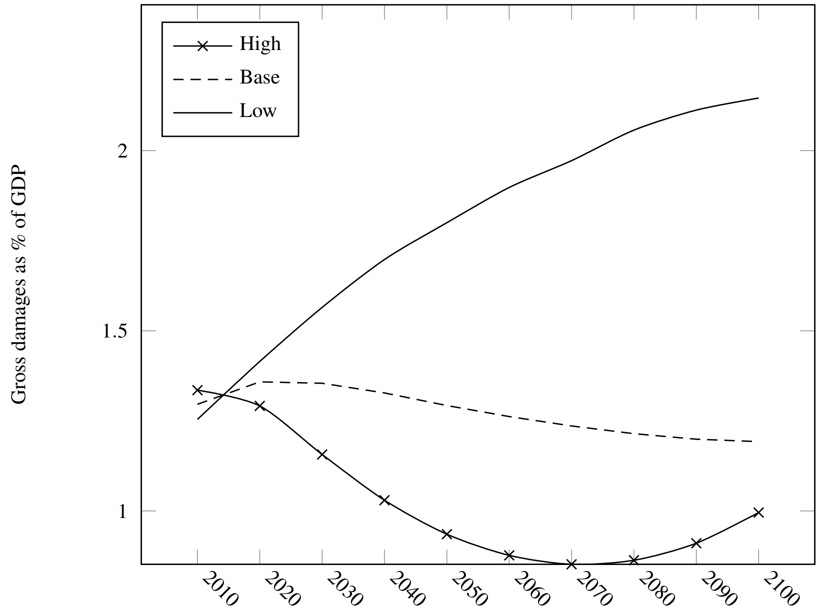


**Figure 12: Gross Damages as % of GDP to growth rate of Total Factor Productivity**

This sensitivity analysis shows the importance of economic growth assumption for the estimates of climate change impacts for Africa.

# 5 Conclusion

Climate change impacts are estimated to be particularly large for Africa, where the exact magnitudes will largely depend on global mitigation efforts. In this paper, we analyse the effect of the Paris climate change agreement in terms of climate change damages and adaptation costs in different African regions.

Here, a new Integrated Assessment Model (IAM) for AFRICA is developed, namely AD-AFRICA. AD-AFRICA is calibrated based on recent climate impact literature focusing on African countries. The impacts are either a function of global temperature change or global sea level rise. The model includes all countries in Africa, aggregated into five regions; Eastern, Western, Southern, Northern and Central Africa. Several key impact sectors are explicitly included in the model; agriculture, fishery, road infrastructure, tourism, health (mortality and morbidity), water and coastal. In the AD-AFRICA framework climate change will create initial impacts (gross damages) which can be reduced through the use of adaptation resulting in actual damages felt (residual damages). Four climate change scenarios are included in the analysis; the Intended Nationally Determined Contributions (INDC) of the Paris agreement, the below $2^0$C (RCP2.6) corresponding to article 2(a) of the Paris agreement, current policy reference and above $4^0$C (RCP8.5).

Our results suggests that, the mitigation commitments of the Paris Agreement (INDCs) decrease climate impacts in Africa considerably compared to current policies. However, increasing mitigation effort to achieve the below $2^0$C goal will result in significantly more damage reduction compared to the INDCs. In fact the impact of the INDCs compared to current policies is smaller than the impacts of the 2 $^0$C compared to the INDCs. This result highlights the importance of addressing the issue of the emissions gap between the Paris agreement's commitments and its goal.

According to our results, adaptation remains an important policy measure even under the most stringent mitigation pathway. This reflects the need for effective climate change policies to not only include both adaptation and mitigation but to consider adaptation and mitigation simultaneously in policy making. Our results suggest that adaptation policies focusing on the building of proactive measures to ensure effective future protection are of high importance in Africa.

We find substantial variation in the climate change impacts between the sectors investigated where if the Carbon Fertilization Effect (CFE) is included in the agriculture sector, the health impacts dominate, particularly in the short run. The health impacts decline over time due to economic growth where it is assumed that economic growth improves the health infrastructure, enabling effective treatment. Towards the end of the century, tourism and agriculture damages became prominent and overshadow health impacts. Considering the importance of the agriculture sector in African economies, we further investigate the extent of climate change impacts without the CFE. Without CFE effect, the agriculture impacts are considerably higher and increase significantly over time.

In AD-AFRICA the level of tourism and agricultural impacts depends on the relative contribution of the tourism and agricultural sectors to regional GDP. Though the reliance of African economies on these sectors decreases as they develop, our findings indicate that tourism and agriculture will continue playing a major role in African economies. These findings suggest a need for countries in African to diversify their economic dependence away from rain fed agriculture and weather related tourism.

Climate change impacts vary across regions due to differences in the level of economic growth and regional characteristics. According to our impact results, Eastern, Western and Central Africa should focus their long term planning and policy priority on the health sector, while Southern Africa should focus on tourism and Northern Africa on coastal.

We further examine the possible consequences of the US withdrawal from the Paris climate change Agreement. The US withdrawal will increase temperature by 0.1 $^0$C in 2100. This would further increase the emissions gap resulting in a larger climate change burden for Africa. Our estimates show the US exit would increase gross damages in Africa by 87 US \$ Billions in 2100. This highlights the importance of the US in global mitigation agreements and the impacts of US policy on other regions.

These results should be interpreted with caution, keeping the limitations and assumptions of IAMs in general and AD-AFRICA in particular in mind. Firstly, though the impact calibration in AD-AFRICA represents a significant improvement on the literature, it is limited to those impacts and sectors for which sufficient and reliable data is available. Therefore, many other impacts such as extreme events, forests, energy, and conflicts are not included in this analysis. In addition, interactions between impacts and production sectors are not considered here. Many sectors (e.g. agriculture and water) will create impacts throughout the economy. These so called economy wide or general equilibrium impacts are not considered in this case. Moreover, impacts are presented as a percentage of African or regional GDP, this hides the much larger impacts at a country or local level. For example, impacts in the coastal sector may seem small on a regional scale, but for coastal areas these impacts are disastrous. Finally, uncertainty is not explicitly included in this analysis. Uncertainty in all of the climate economy interactions, mean that estimates are likely to deviate from actual outcomes in the future.

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## Appendix A Description of the AD-AFRICA economic module

AD-Africa model consists of N regions in Africa where each region is represented by $n = 1, 2, 3......., N$. The time horizon in the model is indexed by $t = 1, 2, 3......., T$. We assume each region in Africa maximises its social welfare function which is defined as;

$$\sum_{t=1}^{T}\sum_{n=1}^{N}\Big(U_{t,n}[c_{t,n}, L_{t,n}]\Big)rr_t \tag{A.1}$$

Where $U_{t,n}$ is total utility for each region $n$ and each period $t$ and $(L_{t,n})$ represents the population size . $rr_t$ is given as;

$$rr_t = (1+\rho_t)^{-t} \tag{A.2}$$

Where $\rho_t$ is the social rate of time preference. In the AD-AFRICA model, utility is represented by a power function which of consumption per capita $(c_{t,n})$ weighed by population size $(L_{t,n})$. Given as;

$$U_{t,n}[C_{t,n}, L_{t,n}] = [C_{t,n}^{1-\varepsilon}/1-\varepsilon]L_{t,n} \tag{A.3}$$

Where $\varepsilon$ is the elasticity of marginal consumption. Output before damages $(Y_{t,n})$ is represented by Cobb-Douglas production function of capital $(K_{t,n})$ and labour $(L_{t,n})$

$$Y_{t,n} = A_{t,n}L_{t,n}^{1-\alpha}K_{t,n}^{\alpha} \tag{A.4}$$

Where $A_{t,n}$ is the total factor productivity (TFP) per time period and for each region. In AD-AFRICA framework climate change will create initial impacts (gross damages) which can be reduced through the use of adaptation measures resulting in actual damages felt (residual damages). The climate change impacts on GDP are modelled as a percentage decrease in production due to the modelled impacts.

$$YNET_{t,n} = (1-D_{t,n})[A_{t,n}L_{t,n}^{1-\alpha}K_{t,n}^{\alpha}] \tag{A.5}$$

Where $YNET_{t,n}$ represents output net of damages and $D_{t,n}$ are the net damages from climate change. The net damages are the total damages from impacts defined as the sum of residual damages $(RD_{t,n,i})$ and adaptation costs $(PC_{t,n,i})$ per impact $(i)$ and for each region.

$$\sum_{i=1}^{I}D_{t,n} = RD_{t,n,i} + PC_{t,n,i} \tag{A.6}$$

In the model, consumption $(C_{t,n})$ is the residual of net output and investments$(I_{t,n})$:

$$C_{t,n} = YNET_{t,n} - I_{t,n} \tag{A.7}$$

Capital accumulation $K_{t+1,n}$ is defined by:

$$K_{t+1,n} = (1 - \delta_k) + I_{t,n} \tag{A.8}$$

Where $\delta_k$ is the depreciation rate.

## Appendix B Description of the AD-AFRICA impact and adaptation modules

Concerning climate change impacts, initial damages before adaptation are referred to as gross damages and are estimated for each of the impacts and regions denoted by $i$ and $n$ respectively. These gross damages $(GD_{t,n,i})$ are a function of either global average atmospheric temperature change $(T_t)$ [9] or sea level rise $(SLR_t)$ as shown;

$$GD_{t,n,i} = \alpha_{1,n,i} \cdot T_t + \alpha_{2,n,i} \cdot T_t^{\alpha_{3,n,i}} \tag{1}$$

$$GD_{t,n,i} = \alpha_{1,n,i} \cdot SLR_t + \alpha_{2,n,i} \cdot SLR_t^{\alpha_{3,n,i}} \tag{2}$$

Where $\alpha_{1,n,i}$ are region and impact specific damage coefficients calibrated from the impact literature. Hence, each sector has a unique gross damage function , see appendix C for a description of the sectoral functions.

In the AD-AFRICA model, these damages can be reduced through the use of adaptation. We assume the following relationship:

$$RD_{t,n,i} = \frac{GD_{t,n,i}}{1 + P_{t,n,i}} \tag{3}$$

Where $P_{t,n,i}$ is the total level of protection (adaptation) per region per impact, $RD_{t,n,i}$ and $GD_{t,n,i}$ are the residual and gross damages respectively. This functional form is chosen as it limits the fraction by which the gross damages can be reduced to the interval of 0 to 1. When total protection reaches infinity, all gross damages are reduced (the residual damages are zero) and when no protection is undertaken no gross damages are reduced (residual damages equal gross damages). This functional form also ensures decreasing marginal damage reduction of protection, where the more adaptation measures applied the less effective an additional measure will be. This is assumed as more efficient measures of adaptation will first be applied whereas less effective measures will follow.

The two forms of adaptation are aggregated together using a Constant Elasticity of Substitution (CES) function. Here the elasticity of substitution is calibrated to reflect the observed relationship between the

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[9] Global temperature change is used here as opposed to regional as most impact assessment are based on global temperature change and not regional.

two forms. This function is given as follows:

$$P_{t,n,i} = \gamma_{1,n,i} \times (\gamma_{1,n,i} SAD^{\rho_A}_{t,n,i} + \gamma_{2,n,i} FAD^{\rho_A}_{t,n,i})^{\frac{\gamma_{1,n,i}}{\rho_A}} \tag{4}$$

Where $SAD_{t,n,i}$ and $FAD_{t,n,i}$ are the total amount of adaptation capital stock (proactive) and the amount spent on flow (reactive) adaptation respectively for each impact and region. Furthermore, $\rho_A = \frac{\sigma-1}{\sigma}$ , where $\sigma$ is the elasticity of substitution. Adaptation capital stock is built up as follows:

$$SAD_{t+1,n,i} = (1-\delta_k^5) SAD_{t,n,i} + IAD_{t,n,i}, \tag{5}$$

Where $\delta_k$ is the depreciation rate and $IAD_{t,n,i}$ are the investments in stock adaptation ($SAD_t$). The total adaptation costs in each period are thus;

$$PC_{t,n,i} = FAD_{t,n,i} + IAD_{t,n,i}, \tag{6}$$

# Appendix C Description of the AD-AFRICA sectoral impact equations

## C.1 Agriculture

Equation 7 is the gross damage function for each crop, where $cro$ stands for crops (maize, rice, wheat and soy), $\alpha_{1,n,cro}$ denotes region and crop specific damage coefficients, $t$ represents time periods, $n$ represents regions and $Q$ denotes production for each crop. $T_t$ represents temperature change compared to 1900 and $t_0$ is the threshold temperature below which there is benefit of climate change through increased $CO_2$ fertilisation. Equation 8 describes the development of agricultural production over time in the absence of climate change. Where $q_{0,n,agri}$ is the initial per crop production as a fraction of total output. $y_{1,n}$ and $y_{t,n}$ are the first period and projected levels of per capita income respectively. $\varepsilon$ is the income elasticity of agriculture Lastly, $GD_{t,n,agric}$ is the gross damage for the agriculture sector which sums gross damages over all crops.

$$GD_{t,n,cro} = Q_{t,n,cro} \cdot \alpha_{1,n,cro} \cdot T_t + \alpha_{2,n,cro} (\frac{T_t}{t_0})^{\alpha_{3,n,cro}} \tag{7}$$

$$Q_{t,n,cro} = q_{0,n,cro} \cdot \left({}^{y\text{"}1\text{"},n}/{}_{yt,n}\right)^{\varepsilon} \tag{8}$$

$$GD_{t,n,agric} = \sum_{cro} GD_{t,n,cro} \tag{9}$$

## C.2 Tourism

Equation 10 is the gross damage function for the tourism sector, where $tour$ represents tourism and $\triangle TA_{t,n}$ is the change in international tourism income resulting from temperature change.

$$GD_{t,n,tour} = \triangle TA_{t,n} \tag{10}$$

The change in total arrivals is calculated as;

$$\triangle TA_{t,n} = Q_{tour,t,n} \cdot (TAncc_{t,n} - TA_{t,n}) \tag{11}$$

Where $TAncc_{t,n}$ is the international tourist arrivals without climate change, $TA_{t,n}$ is the international tourist arrivals with climate change and $Q_{tour,t,n}$ is the tourism income (or production from tourism), which decreases with economic growth as in the agricultural sector defined in Equation (8) above. International tourist arrivals is calculated using the following statistically estimated relationship:

$$TA_{t,n} = exp(la_{co} + (tc_{co} + T_t) - (tco_{co} + T_t^2) + cl_{co} + log(YYCO_{t,co})/L_{t,co}) \tag{12}$$

Here, $la_{co}$ is land surface area in kilometre square (km2), $cl$ is the length coastline in km2, $tco$ is the first period (2010) average annual temperature, $T_t$ is temperature change, $YYCO$ is the country wise regional GDP in dollars and lastly $L$ is the initial population per region. Adaptation to climate impacts in tourism has a limited potential to reduce initial impacts. Literature on adaptation in the tourism sector for most African countries is lacking. Therefore, we conservatively estimate that gross damages from tourism can be reduced by 10% through adaptation.

### C.3 Fishery

Gross damages in fisheries are given by

$$GD_{t,n,fish} = Q_{t,n,fish} \cdot \alpha_{1,n,fish} \cdot T_t \tag{13}$$

Where the gross fishery product is given by ($Q_{t,n,fish}$) and $fish$ denotes the fishery sector. Adaptive capacity in the fishery sector for Western Africa is relatively low. In the model we estimate 30% and 40% as adaptation levels for Western and Northern regions respectively.

### C.4 Coastal

The Gross damages associated with coastal impacts are given as a quadratic function of Sea level rise;

$$GD_{t,n,coast} = \alpha_{1,n,coast} \cdot SLR_t + \alpha_{2,n,coast} \cdot SLR_t^2 \tag{14}$$

The above $coast$ represents coastal impacts and $SLR$ represents sea level rise.

## C.5 Road infrastructure

The impacts associated with road infrastructure are expressed as a fraction of total output as follows.

$$GD_{t,n,road} = \alpha_{1,i,road} \cdot {}^{T_t}\!/\!_{Y_{t,n}} \tag{15}$$

$GD_{t,n,road}$ is the gross damage function for road sector.

## C.6 Water

Using Kirshen (2007) we express water sector impact costs as a fraction of GDP for each region. We treat these as adaptation costs and assume that the potential damage costs (gross damages) would be higher than adaptation costs by a factor range between 1.2-1.4 depending on region vulnerability to water scarcity. Following the estimated damage costs, we assume a power function to depict relationship between temperature change and water sector for each region as follows;

$$GD_{t,n,water} = \alpha_{2,n,water} \cdot T_t^{\alpha_{3,n,water}} \tag{16}$$

## C.7 Health: mortality and morbidity

The current assessment adopts the same assumption and describes the relationship between climate change and human health for each region (n) using a function form shown below;

$$deaths_{t,n,d} = dpar^{1}_{n,d} \cdot T_t^{dpar^{2}_{n,d}} \cdot \left({}^{y_{1,n}}\!/\!_{yt,n}\right)^{dpar^{3}} \cdot l_{t,n} \tag{17}$$

Here the risk of additional death for each disease increases with temperature and decreases with economic development with an elasticity of -0.85 ($dpar^3$) adopted from FUND ((Tol (2008))). $d$ represents the diseases, $y_{1,n}$ and $y_{1,n}$ denotes per region current and projected income respectively. While $l_{t,n}$ represents population projections and $deaths$ is additional estimated deaths due to increase in temperatures. We use this function to calibrate mortality and morbidity gross damages for each region as defined below.

$$GD_{t,n,mort} = sum_d(deaths_{t,n,d}) \cdot 200 \cdot {}^{c_{t,n}}\!/\!_{Y_{t,n}} \tag{18}$$

We use year of life lost due to premature death (YLL) for morbidity estimation.

$$YLL_{t,n,d} = dpar^4 \times deaths_{t,n,d} \tag{19}$$

Where $dpar^4$ parameter is calculated using Disability-adjusted life years (DALYs) and the estimated number of deaths per disease based on data from WHO burden of disease (WHO ((accessed 2015))).

Therefore morbidity is;

$$GD_{t,n,morb} = sum_d(YLL_{t,n,d}) \cdot 0.8 \cdot {}^{c_{t,n}}\!/_{Y_{t,n}} \tag{20}$$

Where, *mort* and *morb* stands for mortality and morbidity. Here following FUND death is valued at 200 per capita and morbidity is 0.8 of per capita income. Current and projected data on population and income per capita are drawn from (WDI ((accessed 2016))) and ((AFDB ((2011))) respectively.

Adaptation has a large potential to decrease impacts in this sector at a relatively low cost, here calibration of adaptation costs is done following the risk assessment for infectious diseases in Africa from AR5 WGII.