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Current Climate Variability and Future Climate Change: Estimated Growth and Poverty Impacts for Zambia

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Abstract

Economy-wide and hydrological-crop models are combined to assess the economic impacts of historical climate variability and future anthropogenic climate change in Zambia. Accounting for uncertainty, results indicate that, on average, current variability reduces gross domestic product by 4% over a 10-year period and pulls 2% of the population below the poverty line. Socioeconomic impacts are much larger during major drought years, thus underscoring the importance of extreme weather events in determining climate damages. Climate change scenarios draw on projections for 2025. Results indicate that, in the worst case scenario, damages caused by climate change are half the size of those from current variability. The paper concludes that current climate variability, rather than climate change, will remain the more binding constraint on economic development in Zambia, at least over the next few decades.

1. Introduction

Climate variability threatens households' livelihoods and undermines economic development, especially in Sub-Saharan Africa, where most countries rely on rainfed agriculture—a sector highly exposed to climate risk. Extreme weather events, such as droughts and floods, also cause substantial socioeconomic damage. Despite our experiences with historical climate variability, most attention today is given to anthropogenic climate change (i.e. long-run changes caused by human activity). The possibility that these future changes might exacerbate the damages caused by current variability has heightened uncertainty and captured the attention of policy makers at national and international levels.

In this paper we compare the incremental damage from future climate change with those already being caused by current climate variability. We develop an analytical framework linking hydrological-crop (HC) models to a recursive dynamic computable general equilibrium (CGE) model, and use this framework to estimate climate impacts on economic growth and household income poverty.

Ours is not the first study to combine biophysical and economic models to evaluate climate impacts. However, previous studies focus on extreme weather events, climate variability, or climate change, without jointly evaluating these phenomena. For instance, Pauw et al. (2010) combined hydro-meteorological and CGE models to assess droughts and floods in Malawi, and Block et al. (2008) used a multi-market model of Ethiopia that linked rainfall and crop yields to compare economic outcomes under static and variable climate patterns. While adopting comparable frameworks to address current climate variability, neither study considers anthropogenic climate change. Conversely,

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Arndt et al. (2011) combined sector models with a CGE model to estimate climate change impacts in Mozambique, but did not compare these with current climate variability. Our study extends previous work by jointly estimating and comparing relative impacts of current and future changes and extreme weather events.

We apply the models to Zambia—a typical low-income, landlocked country in Sub-Saharan Africa with a history of erratic economic growth, part of which is attributable to climate variability. We first review Zambia's climate characteristics (section 2) before describing the modeling framework and our treatment of uncertainty and climate change projections (section 3). Model results are first presented for current climate variability and extreme weather events (section 4), and then for future climate change (section 5). We conclude by summarizing our findings and discussing areas for further research.

2. Zambia's Climate Characteristics

Precipitation and Evapotranspiration

Climates can be characterized by intra-annual distributions and inter-annual variations in precipitation and temperature. Zambia has a moderate climate with temperatures rarely exceeding 35°C. Most rainfall occurs during the 6-month summer season when crucial smallholder staple maize is grown. Only large-scale commercial farms have the irrigation needed to grow wheat or sugar cane during the dry season.

Five agro-climatic zones are defined using monthly observations from 30 weather stations for 1976–2007 (see Figure 1). Climate data are aggregated into zones using the "influencing domain" of each station (i.e. the Thiessen polygon whose boundary defines the area closest to each station relative to other stations). Average annual rainfall generally declines from north to south (see Table 1). We calculate "reference evapotranspiration" (ETo) at each station using the Penman–Monteith equation—a standard method for determining the water transported from the soil to the atmosphere (Allen

Figure 1. Agro-climatic Zones, Weather Stations and Thiessen Polygons

Table 1. Characteristics of Zambia's Agro-Climatic Zones, 1976–2007

	Annual average (mm)		*Coefficient of variation*	
	Precipitation	*Reference Evapotranspiration*	*Precipitation*	*Reference Evapotranspiration*
Zone 1	786	1689	0.180	0.036
Zone 2	818	1624	0.203	0.032
Zone 3	941	1847	0.171	0.031
Zone 4	930	1619	0.152	0.035
Zone 5	1228	1546	0.094	0.021

et al., 1998). From this we measure crop water requirements which, in turn, determine the effect of water availability on crop yields. In contrast to rainfall's declining north-to-south trend, ETo increases north-to-south. This indicates that rainfall is lowest where water requirements are highest, thus exposing rain-fed agriculture in the south to greater risk of yield losses (or crop failure during droughts).

Inter-annual rainfall variation is highest in the drier southern zones (see the coefficient of variation (CV) in Table 1). Assuming annual rainfall follows a normal distribution, then the quantile function of the CV distribution implies that in Zone 2, for example, there is about a 30% chance that rainfall in a year is 20% (i.e. 164mm) above or below the mean (i.e. 818mm). This indicates potential droughts (floods) depending on the spatial and intra-annual distribution of rainfall, particularly within the rainy season. Finally, Zone 2 has a higher CV than Zone 1, despite slightly higher average annual rainfall, thus confirming these two zones' exposure to weather risk and extreme events.

Extreme Weather Events

Droughts are complex phenomena and so an index is often used to measure their severity. For agriculture, drought indices typically reflect the amount of soil water available to the crop, rather than focusing on rainfall deficits. We use a "Palmer Z Index" as a drought severity metric (see Alley, 1984). Monthly indices are calculated for each zone, and averaged over the wet season to create annual indices for the 1976–2007 harvest years. A negative (positive) index value indicates dry (wet) conditions. As shown in Table 2, threshold values categorize growing seasons into severe dry years (–1.5), moderate dry years (–0.5), normal years, moderate wet years (0.5) and very wet years (1.5).

A drought's spatial extent is important for agriculture since simultaneous drought conditions over large areas complicates mitigation efforts, including supplementing drought-afflicted markets with supply from less-affected regions. Table 2 reports frequencies of simultaneous weather events across zones. The worst drought during 1976–2007 occurred in the 1991/92 season when Zones 1–3 simultaneously experienced severe droughts. Other severe droughts occurred in Zones 1 and 2 during 1994/95 and 2004/05 and in Zone 2 during 1986/87. These four seasons represent the major drought years in historical data. By contrast, moderate droughts occurred more often and affected larger areas. "Normal" weather (i.e. an index between –0.5 and 0.5) never occurred simultaneously in more than three zones during 1976–2007, reflecting

Table 2. Occurrences of Extreme Climate Events in Zambia, 1976–2007

	Number of agro-climatic zones simultaneously affected				
	5	*4*	*3*	*2*	*1*
Severe dry ($Z \leq -1.5$)	0	0	1 (92:1–3)	2 (95:1–2; 05:1–2)	1 (87:2)
Moderate dry ($-1.5 < Z \leq -0.5$)	1 (94:1–5)	4	4	4	7
Normal ($-0.5 < Z \leq 0.5$)	0	0	6	11	10
Moderate wet ($0.5 < Z \leq 1.5$)	0	4	5	2	9
Very wet ($Z > 1.5$)	0	1 (78:1–4)	0	1 (81:1,3)	4 (79:5; 89:2; 97:2; 04:3)

Note: Averaged monthly Palmer *Z* Index in maize growing period (November to March); terms in parentheses indicate the year and zones in which events occurred (e.g. "1 (92:1–3)" means one event occurred in 1992 affecting Zones 1–3).

Zambia's proneness to extreme weather events. Finally, wet events occur less frequently than droughts in Zambia. Only in 1977/78 were four zones simultaneously affected by "very wet" conditions.

Two conclusions can be drawn. First, Zambia is prone to droughts and floods, with a high probability of at least one zone experiencing abnormal weather events in any given year. Secondly, the central and southern regions of the country (i.e. Zones 1–3) are especially prone to extreme events, whereas Zone 5 has relatively stable weather conditions with no severe droughts and only one wet season over the period 1976–2007. In the following sections we will develop and use spatially disaggregated models to translate zonal climate variability and extreme events into economic outcomes.

3. Integrated Modeling Framework

Two kinds of models are used to evaluate climate's economic impacts. Hydro-crop (HC) models predict crop yield responses, which are passed top-down to a dynamic computable general equilibrium (DCGE) model to measure changes in sectoral/national production and household incomes/poverty.

Hydro-crop Model

We used a two-stage semi-empirical HC model. First, actual evapotranspiration (ET) is simulated based on a calibrated soil water balance module for the crop's root zone (see Allen et al., 1998). Secondly, crop yield responses to water deficits are estimated using an empirical crop water production module (see Jensen, 1968). Separate models were developed for 12 crops in each agro-climatic zone.

The soil water balance module estimates crops' water requirements expressed as the rate of potential ET. Since accurate field measurements are unavailable, crop-specific water requirements are derived for a reference crop (i.e. alfalfa) and adjusted by a calibrated crop coefficient combining crop transpiration and soil evaporation. This gives crop-specific potential ET under a given set of climate conditions. Based on rainfall and potential ET, the soil water balance module then measures the water flowing into the crop's root zone via precipitation (without irrigation) and the water leaving via ET, surface runoff and deep percolation. The module balances these flows using the root zone available water capacity (AWC) as storage. If the soil water content is above a threshold AWC then actual ET takes place at the potential rate. Otherwise, actual ET is stressed by soil moisture. Surface runoff and deep percolation occur when end-of-period soil water content exceeds AWC. Drawing on historical climate data, this module provides seasonal crop/zone-specific estimates of soil water deficits.

We use the Jensen (1968) crop water production model because it captures monthly climate variations. Crop water sensitivity indices are estimated using ordinary least squares regressions and yield response factors for each growing stage (see the United Nations Food and Agriculture Organization (FAO), 1979). These were mapped to crops' growing periods using the cumulative sensitivity index method (Kipkorir and Raes, 2002). The output of the HC models are yield deviations between zero and one, where one represents the yield during a "normal" climate year.

Computable General Equilibrium Model

We used a neoclassical class of CGE models (see Diao and Thurlow, 2012). These models are often used to examine a range of external and policy changes in developing countries (see, for example, Bautista et al., 2001; Lay et al., 2008; and Jensen and Tarp, 2005). Economic decision-making in a CGE model is the outcome of decentralized optimization by producers and consumers within a coherent economy-wide framework. Production occurs under constant returns to scale. Intermediate demand is determined by fixed technology coefficients (i.e. Leontief demand), while constant elasticity of substitution (CES) production functions allow factor substitution based on relative prices. Profit maximization implies that factors receive income where marginal revenue equals marginal cost. The Zambia model identifies 34 sectors, half of which are in agriculture. Based on the 2004 Living Conditions Monitoring Survey (LCMS), labor markets are segmented into self-employed farm workers; unskilled workers (working both on and off the farm), and skilled workers (off-farm only). Agricultural land is divided into small-scale, large-scale, and urban farms based on crop forecasting surveys (CFS). Small-scale agricultural sectors are further disaggregated across the five agro-climatic zones. Labor is fully employed and mobile, whereas, once invested, capital is fixed by sector. Farmers can therefore change their cropping and livestock patterns and engage more or less intensively in nonfarm activities, thus allowing for some autonomous adaptation to climate changes. However, we limit the extent to which farmers can adjust cropping patterns in response to short-term climate variability, by assuming crop choices are determined at the start of each season, but, once planted, land cannot be reallocated during the growing season. Farmers can, however, reallocate labor time and thereby influence production levels.

Substitution possibilities exist between production for national and foreign markets. This decision of producers is governed by a constant elasticity of transformation (CET) function, which distinguishes between exported and domestic goods. Profit maximization drives producers to sell in markets where they achieve the highest returns based on relative prices. Substitution possibilities also exist between imported and domestic goods under a CES Armington specification (for both final and intermediates usage). Under the small-country assumption, world demand and supply is perfectly elastic at fixed world prices, with the final ratio of traded to domestic goods determined by endogenous relative prices. Production and trade elasticities are drawn from Dimaranan (2006).

The model identifies 15 representative household groups disaggregated by rural/urban areas, farm size (small-scale rural, large-scale rural, and urban), and by zone (for small-scale farmers). Households receive income from producers for use of their factors of production, and then pay direct taxes, save and make foreign transfers (all at fixed rates). Households use remaining income to consume commodities under a linear expenditure system (LES) of demand. The model includes a micro-simulation module with each respondent in the LCMS linked to their corresponding household group in the model. Changes in commodity prices and households' consumption spending are passed top-down from the CGE model to the survey, where per capita consumption levels and poverty measures are recalculated.

Government revenues from direct and indirect taxes are used for domestic/foreign transfers and recurrent consumption spending. Remaining revenues are saved (with deficits being negative savings). All private, public, and foreign savings are collected in a savings pool from which investment is financed. To ensure macroeconomic balance it is necessary to specify a set of "closure" rules. A savings-driven closure balances the savings-investment account, implying that households' marginal savings rates are fixed and investment adjusts to income changes to equate investment and savings. For the current account, we assume that a flexible exchange rate adjusts to maintain a fixed level of foreign savings (i.e. the external balance is held fixed in foreign currency terms). Finally, in the government account, direct tax rate rates are fixed and the fiscal deficit adjusts to equate total revenues and expenditures.

The model is "recursive dynamic", implying that it is solved as a series of static equilibria, with key parameters updated between periods. A recursive model adopts a simple set of adaptive rules in which investors expect prevailing price ratios to persist indefinitely. Sectoral capital stocks are adjusted each year based on previous investment levels, net of depreciation. The model adopts a "putty–clay" formulation, whereby new investment can be directed to any sector in response to differential rates of return, but installed equipment must remain in the sector. Unlike capital, land and labor supply growth is determined exogenously. Sectoral productivity growth is also exogenous. Using these simple relationships to update key variables, we generate a series of growth paths based on different climate outcomes and results from the HC models.

Linking HC and CGE Models

Together the models estimate the economic impact of climate variability over the 10-year period 2006–2016. Since Zambia's future weather patterns cannot be accurately predicted, we use an "index sequential method" to simulate a range of possible patterns using historical data (Prairie et al, 2006). Assuming a circular time series, we draw 32 10-year weather sequences from 32 years of historical climate data for 1976–2007 (i.e. 32 different starting years for each 10-year consecutive sequence in which the first year, 1976, follows the final year, 2007). Individual years within each sequence are not randomly drawn. This method preserves observed inter-annual correlations and captures the full distribution of past variability.

The CGE model's base-year is 2006. We first simulate a baseline scenario assuming "normal" rainfall for each of the 10 years 2006–2016 (i.e. no yield losses caused by climate variability). Yield levels and land allocations expand according to yield potentials from field trials and historical land expansion trends. We call this the "normal rainfall" scenario. We then simulate 32 10-year scenarios reflecting possible weather

Table 3. Impact Channels in the CGE Model

Impact channel	*Affected sectors*	
All 10 years in each of 32 weather sequences		
Crop yields	Rain-fed crops	Yields are reduced based on annual HC model results.
Severe drought years (1983/84, 1986/87, 1991/92, 1994/95 and 2001/02)		
Crop land expansion	Rain-fed crops	Crop land expansion that would take place in a normal year is eliminated in the drought year and remains at zero in the immediate post-drought year.
Livestock stocks	Livestock	Livestock capital declines in drought year and stock growth gradually returns to normal year rates with two-period diminishing lagged effects.
Physical capital accumulation	All sectors	Capital depreciation increases in drought year and gradually returns to normal year levels with two-period diminishing lagged effects.
Major flood years (2006/07)		
Crop land expansion	All crops	Cultivated land area falls in flood year and only returns to pre-flood levels in the subsequent year.

sequences. The crop/zone-specific annual yields estimated by the HC models are imposed on the shift parameter in the CGE model's production functions for each 10-year weather sequence (i.e. on total factor productivity or TFP).

When an extreme weather event year is drawn from the historical data (see section 2) we impose additional shocks on the CGE model (see Table 3). First, harvested land area for drought-affected crops declines during severe drought years (based on historical production data) and slowly recovers over two subsequent years (i.e. the recovery period). Similarly, cultivated land area falls during major flood events (based on World Bank, 2009). Secondly, livestock stocks deteriorate during severe droughts and have a lagged recovery period. Finally, severe droughts reduce physical capital via higher-than-normal depreciation rates. Thus, while crop yield losses are the primary impact channel, the CGE model also captures additional economy-wide impacts caused by extreme weather events.

Climate Change Scenarios

Even with global mitigation measures, current scientific consensus holds that greenhouse gas emissions and atmospheric concentrations will increase over coming decades, causing global mean temperatures to rise (Intergovernmental Panel on Climate Change (IPCC), 2007). Two opposing factors will, in part, determine climate change's impact on agriculture: (1) rising atmospheric CO_2 concentrations may increase crop yields via "carbon fertilization"; and (2) rising temperatures may reduce yields. Given the uncertainty surrounding these opposing impacts, we do not examine the effects of temperature changes and carbon fertilization, but rather focus on hydrological impacts. This is appropriate since changes in water availability are expected to have the largest consequences for agriculture (Rogers, 2008).

Climate change scenarios vary based on global levels of carbon emissions and future economic and demographic developments. We used the "SRES B1a" scenario from the Hadley Centre's coupled atmosphere–ocean general circulation model (GCM) (i.e. henceforth referred to as "HadCM3-B1a"). For this scenario we obtained mean changes in precipitation, minimum and maximum daily average temperature, relative humidity, and wind speed for grid cells in Zambia from the IPCC Data Distribution Center reflecting climatic projections for the period around 2020. The HadCM3-B1a scenario represents a future climate where rainfall declines and temperatures rise throughout Zambia. Mean monthly changes in climate variables from HadCM3-B1a were downscaled to the 30 meteorological stations by finding the grid cell center of the GCM grid nearest to a weather station, and applied to historical monthly weather observations for 1976–2007 in order to construct new climate data reflecting climate changes in 2025. The HC models used these new climate data to estimate yield responses to climate change.

Given the uncertainty surrounding climate projections, two additional (hypothetical) scenarios are used to examine crop yield responses under larger rainfall and temperature changes. In both scenarios we assume that temperatures are 2°C higher each month throughout the country. We then assumed that rainfall is either 15% above or below the observed 1976–2007 series (i.e. the "T2P+15" and "T2P-15" scenarios, respectively). These two hypothetical scenarios are not based on GCM projections but represent more dramatic changes for Zambia over the near-term. They impose uniform changes in temperature and precipitation on historic data from all weather stations. Such hypothetical scenarios are often used to examine responses to wide ranges of climate change (see Zhu et al., 2005).

It is worth noting that the climate change scenarios represent mean changes in future climate and so do not allow for a gradual evolution of climate change. The reason for this simplification is that we use the index sequential method to resample climate series and create the sequences used in our models. This implicitly assumes a stationary climate series. Moreover, we impose future climate changes in 2025 on economic scenarios for the period 2006–2016. We implicitly assume that Zambia does not undergo major structural transformation between 2006 and 2020. Our focus is on the relative size of the impacts from current climate variability and future climate change, and so we do not run the CGE model forward to 2020 before imposing climate change impacts (see Arndt et al., 2011).

4. Results: Current Climate Variability and Extreme Events

Baseline "Normal Rainfall" Scenario

The baseline scenario simulates a normal rainfall sequence for 2006–2016, thus reflecting an optimistic growth scenario for Zambia (i.e. no yield losses from climate variability). Labor supply and capital stocks expand at 2% and 3% per year, respectively. TFP increases by 2% and 3% per year in agriculture and non-agriculture, respectively. Overall, total gross domestic product (GDP) grows at 6.7% per year. Since agriculture grows more slowly, its contribution to total GDP falls from 20.5% to 18.6% by 2016. Rising per capita GDP causes the national poverty headcount to decline from 67.9% to 52.2% by 2016. These trends are consistent with Zambia's recent economic performance and provide an "optimistic" baseline against which we can compare the effects of climate variability.

Impacts on Crop Yields

Figure 2 shows the decline in maize yields for Zones 1–3 caused by historical climate variability during 1976–2007. Relative yields are the ratio of the simulated actual yield

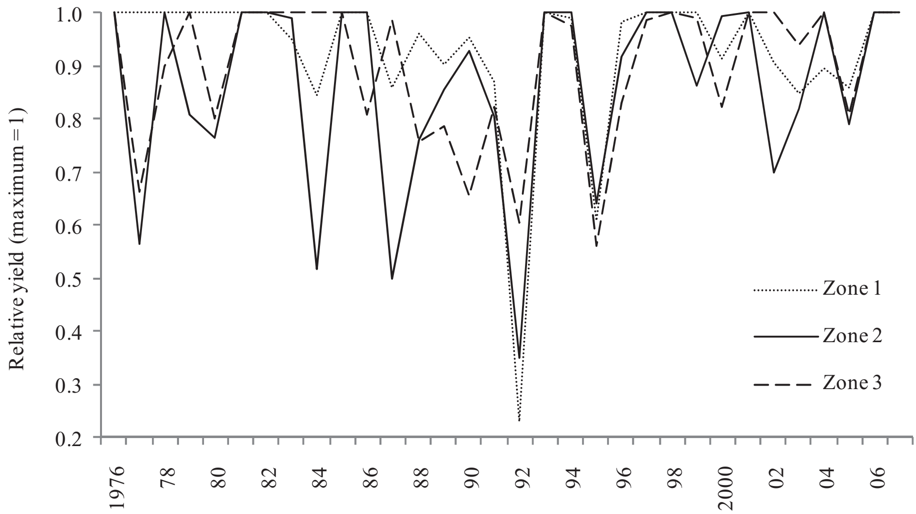

Figure 2. Maize Relative Yields by Agro-climatic Zone, 1976–2007

to the maximum yield achievable without water stress. Maize is chosen as an illustrative crop, but the yield responses of the other rainfed crops follow similar patterns. For Zones 1 and 2, the worst maize yield losses occurred in the 1991/92 season when estimated yields were 77% and 65% below normal yields, respectively. Large yield losses were also found in other seasons for the drier Zones 1–3 (i.e. 1994/95 for Zones 1–3; 1976/77 for Zones 2 and 3; and 1983/84, 1986/87 and 2001/02 for Zone 2). Yield reductions during these seasons ranged between 30% and 50%. Zones 4 and 5 are not shown in the figure since they are less drought-prone than other parts of the country and so their drought-induced crop yield losses are both smaller and less frequent. For example, the largest yield loss in Zone 5 was 14% in 1991/92.

Table 4 summarizes the severity and consequences of droughts and wet events. The table shows the ranges of rainfall; relative maize yield losses; and the frequency of weather events during 1976–2007. It also shows the Water Requirement Satisfaction Index (WRSI), which is the ratio of actual to potential ET during the maize growing season. Each indicator is separated across zones and event categories. For example, the range of growing season rainfall in Zone 1 for all severe drought years is 405–499 mm.

For the drier Zones 1–3, there were only seven or eight out of 32 years (i.e. 1976–2007) in which rainfall during the growing season was within the "normal" range. This indicates a 75–80% chance that, in a given year, there is either a drought or too much rain in at least one of these three zones. Moreover, there is about a one-in-ten chance of a severe drought occurring in Zones 1 and 2, during which yields fell by 14–77% and 21–65%, respectively. The average relative water deficit (i.e. 100—WRSI) is usually not as high as yield losses during severe droughts. Rather it is abnormally low rainfall during critical growing stages that causes substantial yield losses. The table clearly shows that Zones 1–3 are drought-prone, whereas major drought damage is rare in Zones 4 and 5. Moreover, despite being the wettest zone, very wet weather events are also rare in Zone 5, with only one occurrence in 32 years.

Our HC models are for drought impact assessments. Yield losses from floods and water-logging are not assessed, since floods are typically localized short-duration events and their assessment requires high-resolution data. However, drought damage is more important than flood damage for Zambia (World Bank, 2009). Moreover, the analysis

Table 4. Maize Results from the HC Models, 1976–2007

		Palmer Z drought index-based weather classification				
		Severe dry	*Moderate dry*	*Normal*	*Moderate wet*	*Very wet*
Zone 1	Growing period rainfall (mm)	405–499	481–624	632–751	746–902	971–1031
	Maize WRSI (%)[a]	70–96	94–100	96–100	97–100	100
	Maize yield loss (%)[b]	14–77	1–15	0–8	0–10	0
	Frequency[c]	3	8	8	11	2
Zone 2	Growing period rainfall (mm)	401–506	505–623	711–781	761–887	961–1008
	Maize WRSI (%)[a]	75–95	83–100	94–100	92–100	96–100
	Maize yield loss (%)[b]	21–65	0–48	7–19	1–23	0–14
	Frequency[c]	4	9	7	9	3
Zone 3	Growing period rainfall (mm)	585	578–766	765–858	927–1085	1079–1125
	Maize WRSI (%)[a]	86	86–100	88–100	95–100	97–100
	Maize yield loss (%)[b]	40	0–44	1–34	0–21	0–10
	Frequency[c]	1	13	7	8	3
Zone 4	Growing period rainfall (mm)	–	635–781	765–954	910–1058	1113
	Maize WRSI (%)[a]	–	97–100	95–100	95–100	99
	Maize yield loss (%)[b]	–	1–11	0–17	0–20	2
	Frequency[c]	–	11	10	10	1
Zone 5	Growing period rainfall (mm)	–	875–987	960–1158	1136–1314	1290
	Maize WRSI (%)[a]	–	98–100	97–100	100–100	100
	Maize yield loss (%)[b]	–	0–9	0–13	0	0
	Frequency[c]	–	7	18	6	1

Notes: [a]"WRSI" is the ratio of actual to potential ET during growing season; [b]Maize yield losses estimated by HC model; [c]Number of annual occurrences during 1976–2007.

of wet events in Table 4 provides some measure of flood events and shows how yield losses occur during wet years owing to the uneven distribution of rainfall.

Impacts on Economic Growth

Baseline agricultural GDP rises from US$2.1 billion in 2006 to US$3.6 billion by 2016, implying a 5.7% annual growth rate (see "normal sequence" in Figure 3). As described in section 3, we simulate 32 weather sequences drawn from historical climate data. The decline in agricultural GDP caused by climate variability varies by sequence. We report the mean outcome of all sequences ("average sequence") and the results of the worst sequence (defined below). The results confirm agricultural GDP's sensitivity to climate variability. On average, variability reduces agricultural GDP's growth rate by one percentage point from the baseline. Accumulated losses equal US$2.2 billion (undiscounted and measured in 2006 prices), which is almost equal to agricultural GDP in an average year.

The worst rainfall sequence is identified using two criteria: the value of annual rainfall's CV and the frequency of severe drought events. The worst 10-year rainfall sequence occurred between the 1985/86 and 1994/95 seasons. During this period the CV was highest in our historical climate data and the three most severe droughts occurred. The CGE model shows that if the rainfall patterns during 2006–2016 replicated the

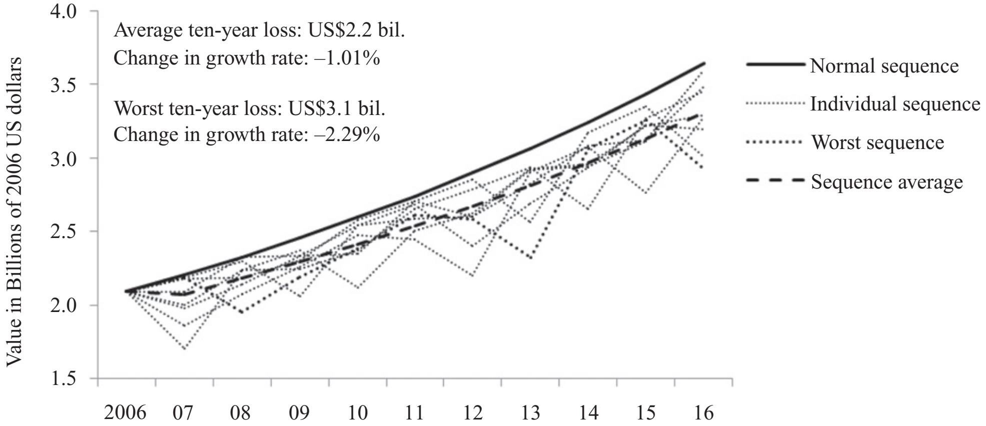

Figure 3. Agricultural GDP Losses Owing to Climate Variability, 2006–16

Table 5. Growth and Poverty Results Under Current Climate Variability, 2006–16

	Average rainfall sequence		*Worst rainfall sequence*	
	Change in annual growth rate (%-point)	*Accumulated 10-year losses (US$m)*	*Change in annual growth rate (%-point)*	*Accumulated 10-year losses (US$m)*
Total GDP	–0.43	4278	–0.90	7088
Agricultural GDP	–1.01	2213	–2.29	3132
Zone 1	–1.28	172	–4.63	302
Zone 2	–1.58	1682	–3.52	2442
Zone 3	–0.86	5	–2.44	9
Zone 4	–0.93	182	–1.64	175
Zone 5	–0.37	158	–0.94	169
	Change in poverty rate in 2016 (%-point)	*Absolute poverty change (1000s)*	*Change in poverty rate in 2016 (%-point)*	*Absolute poverty change (1000s)*
Poverty	2.25	300	4.85	648
Rural	2.05	167	4.25	346
Urban	2.56	133	5.79	303

Note: Ten-year losses are undiscounted cumulative losses for the 10-year period. Since zonal agricultural GDP excludes forestry, total zonal impacts are below national impacts.

worst historical sequence then the accumulated losses in agricultural GDP would be US$3.1 billion. This is almost 50% larger than the accumulated losses under the average rainfall sequence, and is a reduction in average annual agricultural GDP growth by 2.3 percentage points.

Economy-wide impacts are even larger than those on agriculture alone (see Table 5). On average, climate variability causes an accumulated loss in total GDP of US$4.3 billion, which is equivalent to reducing the total GDP growth rate by 0.4 percentage points. Ultimately, Zambia's economy is 4% smaller in 2016 than it would have been without climate variability. Current climate variability therefore has a profoundly negative impact on economic growth. Moreover, damages in the worst sequence are almost twice as large. This substantial contraction reflects the severe droughts that took place in the 1986/87, 1991/92, and 1993/94 seasons, which affected the entire economy.

Table 5 also reports changes in zonal agricultural GDP. Drought-prone Zones 1 and 2 are important for the agricultural economy, generating half of national agricultural GDP and two-thirds of national maize production. Damages from climate variability are largest in these zones. Almost 85% of agricultural GDP losses occur in Zones 1 and 2, whereas Zone 5 is largely unaffected. Economic losses under the worst rainfall sequence are even more concentrated in Zones 1 and 2, with almost 90% of agricultural GDP losses occurring in these two zones.

Impacts on Household Poverty

Climate variability has detrimental effects on incomes and poverty. Figure 4 shows estimated national poverty headcount rates for 2006–2016 (i.e. the share of the population with per capita consumption below the official poverty line). Baseline poverty falls from 67.9% to 52.2% during 2006–2016, which is enough to offset population growth of 2% per year so that the absolute number of poor people falls from 7.44 to 6.96 million. However, climate variability slows poverty reduction and, on average, raises the national poverty rate by 2.3 percentage points higher by 2016. There are thus 300,000 more people living beneath the poverty line in 2016 than there would have been without climate variability. Under the worst rainfall sequence, the national poverty rate is 4.9 percentage points higher in 2016 and there are 648,000 more poor people.

Climate variability affects poverty reduction in both rural and urban areas for two reasons. First, a third of Zambia's urban population engages in agricultural production and so climate variability will affect agricultural revenues and urban incomes. Secondly, food forms a large share of urban consumption baskets. So falling agricultural production causes food prices to rise and reduces real urban incomes. On average, our results indicate that two-fifths of the additional poverty caused by climate variability occurs in urban areas (i.e. 133,000 people out of 300,000 at the national level). This underscores the economy-wide nature of climate variability's impacts, even though our primary impact is via agriculture.

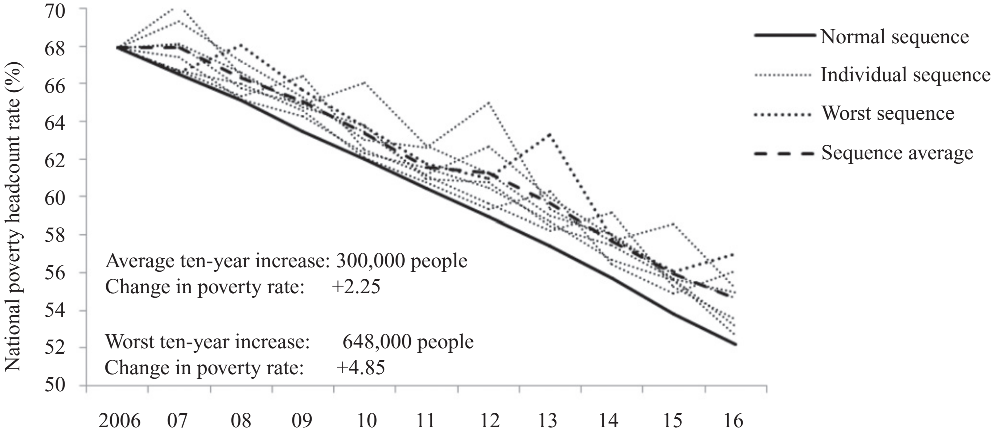

Figure 4. Change in National Poverty Headcount Owing to Climate Variability, 2006–16

Impacts During Extreme Weather Events

The above results report average impacts over 10-year periods. Here we describe the losses occurring during major drought or flood years. We present the outcomes of a severe drought year (1991/92), a modest drought year (1994/95), and a severe flood year (2006/07). To ensure comparability, we adopt the same base year (i.e. the same level and structure of economic activity) and impose the weather shock during the second simulation year (i.e. 2007). This means that we are not estimating the impact of the actual 1991/92 drought, which would require a model calibrated to the 1990/91 season, but rather what the impact would have been if a drought of similar magnitude were to have occurred in 2007.

The impacts of extreme weather events on total and agricultural GDP are reported in Table 6. A severe drought of the same magnitude as one experienced in 1991/92 reduces national agricultural GDP by 22.7% compared with a normal rainfall outcome in the same year. This is mainly due to large declines in agricultural production in Zones 1–3. Falling agricultural production and its knock-on effects causes total GDP to decline by 6.6%. A modest drought like the one in 1994/95 reduces national GDP by 4% and with larger declines in Zones 1–3. By contrast, a severe flood like that of 2006/07 affects zones more evenly but has a less pronounced impact on the overall economy. Thus, while agricultural GDP in Zone 5 declines the most under the severe flood, the impact on other zones is smaller than under even the modest drought, and total GDP declines by only 2.3%.

While broadly consistent, the modeled decline in agricultural GDP during an extreme drought year is smaller than the observed decline in 1991/92 (i.e. 33%). One reason for this difference is the substantial change in the composition of agriculture that occurred between 1991 and 2006 (i.e. the base year for our analysis). Farmers in Zambia increased their production of drought-tolerant sorghum and millet and

Table 6. Extreme Weather Event Results, 2006–16

	Percentage point change in growth or poverty rate during extreme event year		
	Severe drought	*Modest drought*	*Severe flood*
Total GDP	–6.6	–4.0	–2.3
Agricultural GDP	–22.7	–15.7	–9.4
Zone 1	–60.1	–30.8	–7.8
Zone 2	–40.8	–24.0	–13.5
Zone 3	–22.4	–17.3	–5.6
Zone 4	0.1	–12.0	–14.1
Zone 5	2.6	–5.3	–5.7
National poverty	7.5	3.9	2.4
Zone 1	5.6	2.3	0.1
Zone 2	8.2	1.4	0.6
Zone 3	6.5	4.1	1.4
Zone 4	2.8	2.1	3.3
Zone 5	–1.3	–1.0	–0.8

Note: Severe drought reflects climate conditions from 1991/92; modest drought is 1994/95; and severe flood is 2006/07.

reduced maize production, primarily as a result of the removal of unsustainable maize subsidies during the 1990s (see Thurlow and Wobst, 2006). Moreover, non-traditional exports, including sugar-cane and cotton, expanded dramatically, especially in the drought-affected Zones 1, 2, and 4. These crops are more drought-resistant than traditional food crops and also benefit from irrigation. Given these changes, the agricultural sector as a whole has become more drought resistant over time, which is the main reason for the smaller GDP losses in our economic model.

Extreme weather events also adversely affect poor households' incomes. The national poverty rate rises by 7.5 percentage points during the severe drought year. This implies an increase in the number of poor people by 836,000 compared with a normal year. Poverty also rises during a modest drought year by 3.9 percentage points or 435,000 people. Finally, the national poverty rate rises by 2.4 percentage points during a severe flood year, pushing 273,000 more people below the poverty line in that year.

In summary, current climate variability has a large detrimental impact on economic development in Zambia. It reduces agricultural production, especially in the southern and central regions. Agriculture's importance and strong linkages to the rest of the economy means that economic losses from climate variability occur outside of agriculture and rural areas. This underscores the importance of including economy-wide effects when evaluating climate variability. This is especially true for the growth and poverty impacts of extreme weather events. The consequences of these extreme events, particularly major droughts, overshadow the losses caused by average (or year-on-year) climate variability.

5. Results: Future Climate Change

Impacts on Crop Yields

Our three climate change scenarios do explicitly change the variability in historical climate data, but rather change mean climate variables (i.e. the "delta" approach). The impact of mean climate changes on crop yields are analyzed using the HC model. Table 7 reports the mean and average standard deviation of changes in maize yields relative to the estimated yields for 1976–2007. In the HadCM3-B1a scenario, maize yields decline

Table 7. Yield Responses under Climate Change Scenarios

	Changes in maize yields relative to historical yield trends (%)					
	HadCM3-B1a		*T2P-15*		*T2P+15*	
	Mean	*Standard deviation*	*Mean*	*Standard deviation*	*Mean*	*Standard deviation*
Zone 1	–0.9	1.3	–5.8	6.9	3.2	4.4
Zone 2	–1.0	1.4	–5.7	5.8	4.2	5.6
Zone 3	0.1	0.5	–4.5	4.2	3.2	4.5
Zone 4	–1.3	1.3	–3.8	4.1	1.8	2.2
Zone 5	–0.2	0.5	–1.4	2.2	0.5	1.5

Note: HadCM3-B1a is SRES B1a scenario from HadCM3 GCM; T2P-15 and T2P+15 scenarios assume that temperatures rise by 2% and rainfall either rises or falls by 15%.

relative to the historical trend of 1976–2007 in all zones except Zone 3. Since rainfall generally declines in the HadCM3-B1a scenario, this slight increase in Zone 3's maize yield is mainly caused by slight increases in rainfall under the HadCM3-B1a scenario.

From our results we conclude that, compared with the historical period, climate change with less rainfall and higher temperature (i.e. the HadCM3-B1a scenario) leads to a 1% reduction in maize yields by 2025 for Zones 1, 2, and 4 and to small yield changes in Zones 3 and 5. Since the HadCM3-B1a scenario does not capture changes in rainfall variation, the standard deviations of maize yields from historical trends have a similar magnitude to the changes in the mean. Although the HadCM3-B1a scenario causes only small changes in mean yields relative to historical trends, impacts within a particular year can be much larger. For example, in a severe drought year, such as that of 1991/92, maize yields are 4% lower than they were in 1991/92 when future climate change effects were not incorporated.

In the T2P-15 scenario, mean maize yields decline by 4–6% relative in all zones except Zone 5, where they decline by only 1.4%. Again, the magnitude of standard deviations is consistent with the mean change at the zonal level. This implies that there will be an average 4–6% drop in maize yields throughout most of Zambia if rainfall in the future declines by 15% and the temperature rises by 2 degC. In the T2P+15 scenario mean maize yields increase by 3–4% relative to historical trends for Zones 1–3. There is a 2% increase for Zone 4 and a slight increase for Zone 5. In both hypothetical climate change scenarios, the wetter Zone 5 remains fairly resilient to climate changes in terms of crop yield responses to changing rainfall. In contrast, the remaining drier zones experience larger changes in crop yields.

Impacts on Economic Growth and Poverty

In section 4 we used the CGE model to estimate the economy-wide impact of current climate variability by simulating 32 possible 10-year rainfall patterns drawn sequentially from historical data for the period 1977–2007. Here we use a similar approach. Corresponding to each climate change scenario, we adjust historical rainfall data to reflect new weather conditions. The three synthetic datasets now contain the effects of both historical climate variability and future climate change. We then redraw the 32 sequences from each synthetic dataset and compare the average outcomes under these new climate change scenarios with the average outcomes from the previous section which only included the effects of current climate variability. The differences between these average outcomes can be solely attributed to climate change.

The climate change results are reported in Table 8. The top half of the table shows deviations in the mean of all rainfall sequence scenarios from the results of the normal rainfall scenario. As discussed in section 4, if climate variability follows historical patterns without any future climate changes, then the average decline in the annual total GDP growth rate of is 0.4 percentage points. Incorporating the effects of climate change produces mixed results. The decline in total GDP growth is only slightly larger under the HadCM3-B1a scenario, but is much larger under the T2P-15 scenario. Conversely, higher rainfall under the T2P+15 scenario dampens the effects of climate variability, such that the decline in GDP growth is smaller than in the case without climate change. These results indicate that if climate changes cause less rainfall every year, then annual economic growth would decline further by between 0.05 percentage points (HadCM3-B1a scenario) and 0.20 percentage points (T2P-15 scenario). However, with more rainfall, GDP growth increases by 0.14 percentage points (T2P+15 scenario).

Table 8. Growth and Poverty Results under Climate Change Scenarios

	Deviation from the results of the normal rainfall scenario					
	Change in annual growth rate (%-point)		*Accumulated 10-year GDP losses (US$bn)*			
	Total GDP	*Agric. GDP*	*Total GDP*	*Agric. GDP*	*Change in poverty rate* (%-point)	*Absolute poverty change (1000s)*
Mean of 32 rainfall sequences						
No climate change	–0.43	–1.01	–4.32	–2.21	2.25	300
HadCM3-B1a	–0.48	–1.07	–4.69	–2.34	2.49	332
T2P-15	–0.63	–1.32	–6.02	–2.86	3.25	433
T2P+15	–0.29	–0.76	–3.00	–1.69	1.55	207
Worst rainfall sequence						
No climate change	–0.90	–2.29	–7.13	–3.13	4.85	648
HadCM3-B1a	–1.01	–2.55	–7.84	–3.36	5.41	722
T2P-15	–1.31	–3.35	–9.91	–4.07	7.23	965
T2P+15	–0.61	–1.51	–5.08	–2.41	3.16	422

Notes: HadCM3-B1a is SRES B1a scenario from HadCM3 GCM; T2P-15 and T2P+15 scenarios assume that temperatures rise by 2% and rainfall either rises or falls by 15%.

The implications of these seemingly small changes in total GDP's growth rate become more substantial once the effects are accumulated over the 10-year period 2006–2016. For instance, cumulative declines in total GDP in the T2P-15 scenario are US$6 billion (i.e. US$1.7 billion more than that without climate change effects) compared to US$3 billion in T2P+15 scenario (i.e. US$1.3 billion less than that without climate change effects). Even in the more modest HadCM3-B1a scenario, climate change raises the damages already caused by current climate variability by an additional US$0.37 billion. Thus while the economic implications of climate change may appear inconsequential at any given point in time, its gradual impact on GDP becomes more significant over time.

The final two columns of the table report impacts on national poverty rates and the absolute number of poor people. Since climate change affects agricultural production and food prices directly, there is a large difference in poverty outcomes across the three scenarios. Even in the modest HadCM3-B1a scenario the national poverty rate in 2016 is 0.24 percentage points higher. Thus even the small changes in climate expected by 2025 will increase the absolute number of poor people by 32,000 over 10 years. Deviations in poverty rates are also much larger for the two hypothetical climate scenarios.

Overall, the incremental impact of future climate change on economic growth and poverty in Zambia is smaller than that of current climate variability, at least until 2025. Even the damages caused by the more pessimistic climate change scenarios are less than half those of the current climate variability scenarios. However, it should be noted that we did not model changes in climate variability and hence can only provide illustrative results for potential climate change impacts in Zambia. Thus, while average changes over the longer-term are relatively small, there may be large impacts during specific years, especially if there is even less rainfall than during the severe drought years observed in Zambia's history.

6. Conclusion

Using an integrated hydro-crop and CGE modeling framework, we compared the economic impacts of current climate variability and future climate change. Results indicate that, on average, current variability reduces Zambia's agricultural and total GDP by 9% and 4%, respectively, over a 10-year period. Income losses to households mean that an additional 300,000 people remain below the national poverty line as a result of current variability (i.e. 2.3% of the population in 2016). Socioeconomic impacts during extreme weather event years are particularly severe. Results indicate that total GDP falls by 6.6% during a severe drought (i.e. similar to that of 1991/92), and the national poverty rate rises by 7.5 percentage points pulling an additional 836,000 people into poverty during the drought year. These results confirm that current climate variability already presents a significant challenge to future development in Zambia, particularly in the southern and central regions.

We also examined whether climate change will exacerbate or dampen the negative impacts of current variability. Here considerable uncertainty exists, especially regarding changes in future rainfall patterns. Accordingly, we not only used a modest GCM projection, but also simulated two more extreme hypothetical scenarios. We found that climate change damages will be much smaller than those from current climate variability, at least until after 2025. However, differences in rainfall projections influence the size, and to a lesser extent, the direction of economic impacts. For example, if mean rainfall were to fall by 15% throughout Zambia, then climate change would increase the economic losses from current climate variability by 50%. Therefore, even though current climate variability will continue to dominate anthropogenic climate changes over the next few decades, our results suggest that there are still large incentives to address climate change concerns, especially since most anthropogenic climate change is expected to occur after 2025 (IPCC, 2007).

There are at least three areas where our study can be extended. First, we focused on agricultural impacts via crop yields. Recent studies, such as Arndt et al. (2011), found that agriculture may not be the main impact channel for climate change damages, even in low-income African countries. Further work is needed to incorporate other impact channels. Secondly, we considered a range of possible climate change outcomes, but designing robust adaptation strategies requires knowledge of the full distribution of GCM projections (and ideally the relative probability of them being realized). Finally, we allowed only limited autonomous adaptation opportunities, which we felt were appropriate for small-scale farmers' land allocation decisions. However, forward-looking adaptation behavior may be needed in sectors (and countries) that are more developed than Zambia's smallholder agriculture.

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