The Impact of Climate Variability and Change on Economic Growth and Poverty in Zambia

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1. Introduction

Zambia is a low-income country with a history of erratic economic growth. Some of the uneven performance of the economy has been driven by unsustainable policies, adverse global conditions, and pronounced shocks from macroeconomic reforms (Resnick and Thurlow, forthcoming). While the country has performed well since the late 1990s, with positive economic growth and poverty reduction (see Figure 1), growth in agriculture remains volatile despite improvements in the policy environment. This can, at least in part, be attributed to high rainfall variability, or more generally climate variability, in the country. Indeed some of the more substantial declines in economic growth over the last three decades have occurred during major drought years. Climate variability is especially important for the agricultural sector, which is heavily dependent on rainfall due to the country's limited irrigation capacity. Climate variability may also undermine attempts to reduce poverty, since most of Zambia's poor population live in rural areas and are heavily dependent on agricultural incomes. Overcoming climate variability therefore poses a significant challenge to maintaining agricultural growth, significantly reducing poverty, and achieving the Millennium Development Goals. It also heightens concern over potentially negative impacts from climate change. Together climate variability and climate change places considerable pressure on Zambia's government to improve incentives for farmers and for the private sector to invest in infrastructure and improve productivity.

Within this context, a number of key policy relevant questions emerge:

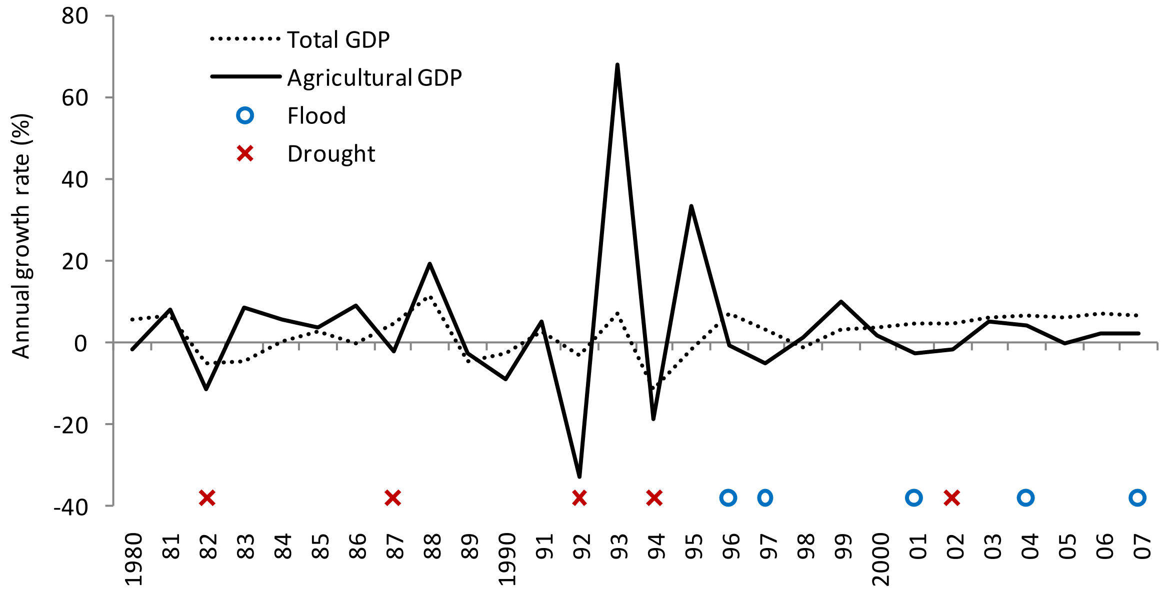
- What is the economic cost of climate variability for both agricultural and national production?
- How does climate variability affect household welfare and poverty at the national level?
- Which regions in the country are most vulnerable to climate variability?
- Will climate change exacerbate or dampen variability and what are its long-term implications for economic growth and poverty reduction in Zambia?

This paper addresses these questions through an integrated framework linking together various hydrological, crop simulation and economic models that draw on Zambia's historical data. The next section reviews temporal, inter-temporal and spatial rainfall patterns in Zambia in the 33 years between 1975 and 2007[2]. Section 3 estimates the impact of Zambia's historical climatic patterns on crop yields using hydrological and crop yield simulation models. Section 4 combines the results from the hydro-crop models and analyzes the impact of climate variability on economic growth and poverty reduction over the next 10 years using an economywide model. Section 5 assesses how climate variability and its

[2] In the following analysis for crop growing season the data period is referred to as 1976-2007 because crop growing season spans two calendar years.

economic impacts may be exacerbated or dampened by climate change over the next 30-50 years. The final section summarizes our findings and suggests policy responses.

Figure 1.1: Annual total and agricultural GDP growth rates, 1980-2007



Notes: World Bank (2008) for 1980-97, and national accounts for 1998-2007 (CSO, 2008).

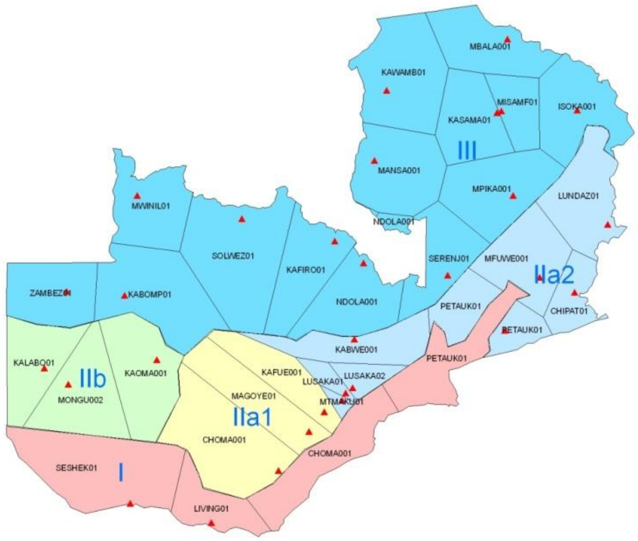
2. Climatic characteristics of Zambia

The high plateau on which Zambia is located ensures that the country has a moderate climate, with summer temperature rarely exceeding 35°C. However, rainfall is unevenly distributed throughout the year, with the majority concentrated in the six months from November to April. This leaves the remaining months almost dry. Accordingly, Zambia has three seasons: 1) a rainy season in summer from November to April; 2) a cool dry winter season from May to August; and 3) a hot dry season in September and October. Hence, for most rain-fed crops the growing season is the rainy season. Moreover, much of the country's socioeconomic life is dominated by the onset and end of the rainy season, and the amount of rain it brings.

Agro-climatic characteristics in any country or sub-national region are primarily determined by intra-year distributions and inter-year variations in rainfall and temperature. The rains of Zambia are brought by the Intertropical Convergence Zone which is located north of the country in the dry season. It moves southwards in the second half of the year, and northwards in the first half of the year. Given Zambia's altitude, its temperatures are lower than coastal regions at similar latitudes. Analysis of the causes of Zambia's climate and agriculturally-important weather events are beyond the scope of this study. For this study, monthly weather observations were made available by the Zambia Meteorological Department, and data for 1976-2007 at 30 weather stations were used (see the red markers in Figure

2.1).[3] These 30 meteorological stations are located in five distinguished agroecological zones that later form the spatial unit for our analysis.

Figure 2.1: Zambia's agroecological zones, meteorological stations and Thiessen polygons



Notes: Thiessen Polygons were created to define the influencing domain of each of the thirty meteorological stations. Red triangles mark the locations of meteorological stations.

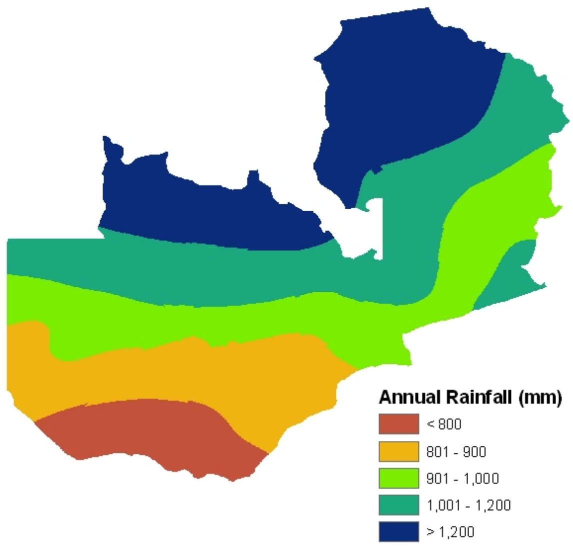
2.1 Spatial distributions of annual rainfall and evaporation

Figure 2.2 shows average annual rainfall at the 30 weather stations in Zambia during 1976-2007 interpolated to 1km pixels. There is a downward gradient of annual rainfall from the north to the south of the country, with the highest rainfall in the northwest and northeast (generally above 1200 mm) and the lowest in the southwest (generally below 800 mm).

'Reference evapotranspiration' (ET_O) is the evapotranspiration potential or atmospheric water demand of a reference grass (Allen et al., 1998). This measure provides the basis for estimating crop water requirements, which is essential information if we are to estimate how changes in rainfall or water availability affect crop yields. We calculate monthly ET_O using weather data from the 30 stations. Mean annual ET_O values were then interpolated to 1km pixels, as shown in Figure 2.3. The results indicate that, in contrast to the north-to-south declining trend of rainfall, ET_O increases from the north to south, especially in the southwest part of the country. This suggests rainfall is lowest in areas where crops water requirements are highest, thus exposing rain-fed agriculture in the south to considerable risks of yield losses or even crop failure during droughts.

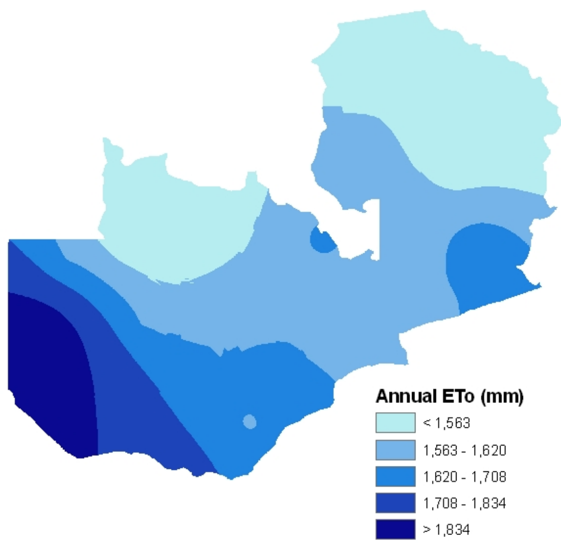
[3] There is a tradeoff between station coverage and the lengths of observations of selected stations. The choice of 30 stations' data for the period 1975-2007 was thus a balance between cross-sectional and time-series coverage.

Figure 2.2: Average annual rainfall, 1975-2007



Source: Authors' calculations using historical rainfall data from the Zambia Meteorological Department.
Notes: Generated from 1km pixel averaged annual rainfall interpolated from 30 weather stations.

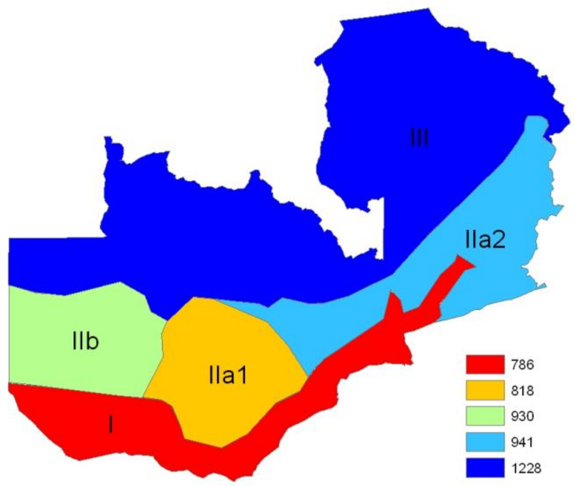
Figure 2.3: Average annual reference evapotranspiration, 1975-2007



Source: Authors' calculations using historical rainfall data from the Zambia Meteorological Department.
Notes: Generated from 1Km pixel averaged annual ETo interpolated using ETo calculated for thirty weather stations.

The main objective of this study is to analyze the impact of climate variability on Zambia's economy of which agriculture is an important component. Thus, it is necessary to aggregate the country into five agroecological zones, each of which has different climate patterns. Zone I covers most of Southern province and parts of Lusaka and Eastern provinces. Zone IIa is subdivided into two smaller zones because of differences in rainfall patterns (see discussion below). Zone IIa1 covers the capital city Lusaka and the eastern parts of Central province, while Zone IIa2 includes the western parts of Central province and most of Eastern province. Zone IIb comprises almost entirely Western province. Finally, Zone III, which is the largest one in terms of geographic size, includes the Copperbelt, North Western, Luapula and Northern provinces. In this study, rainfall and other meteorological data were aggregated to these five zones, taking into consideration the influencing domain of each weather station (Figure 2.1). Zonal level average annual rainfall is presented in Figure 2.4, which shows a similar pattern as in Figure 2.2, with the highest rainfall in the northern Zone III, and the lowest rainfall in the southern Zone I. Zone IIa1 has a mean annual rainfall of 818 mm, which is only slightly higher than Zone I. By contrast Zones IIa2 and IIb have higher annual rainfall at 941mm and 930mm respectively. These differences highlight the importance of separating the eastern and western parts of Zone IIa, especially since most of Zambia's economic activity takes place near Lusaka.[4]

Figure 2.4: Average annual precipitation by agroecological zone, 1976-2007 (mm)



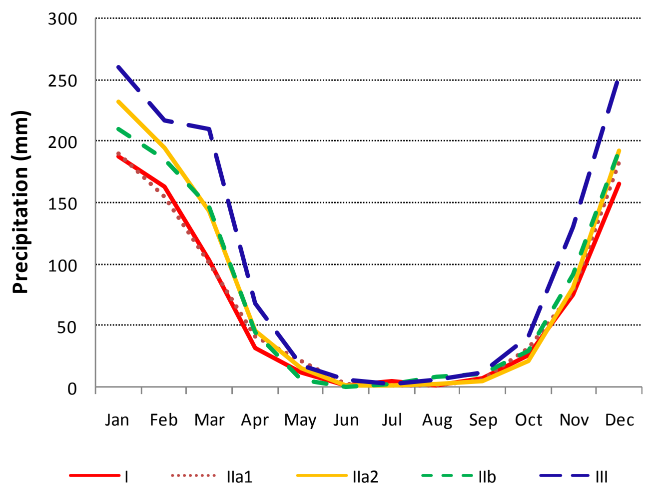
Source: Authors' calculations using historical rainfall data from the Zambia Meteorological Department.

2.2 Intra-annual distribution and inter-annual variations of rainfall and evaporation

The distribution of rainfall and temperatures during a year determines the growing season of annual crops and influences their yields, especially those cultivated under rain-fed conditions. Figure 2.5 shows monthly rainfall distributions in Zambia's five agroecological zones. It shows that most of the rainfall in each of the five zones is concentrated between November and April (the rainy season), with virtually no rainfall from May to September (the dry winter season). Although the 20-40mm rainfall in October marks the end of the dry season, the depletion of soil moisture during the dry season may prevent immediate crop planting in this month.

[4] Appendix C describes the economic structure of the five agroecological zones.

Figure 2.5: Mean monthly precipitation in agroecological zones, 1976-2007



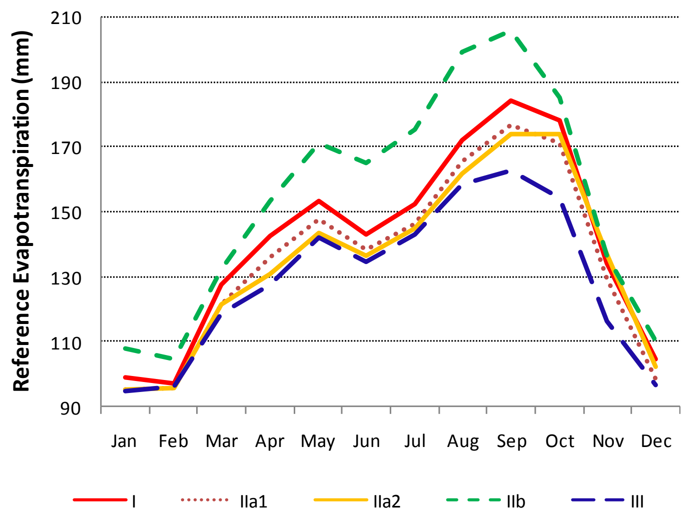
Source: Authors' calculations using historical rainfall data from the Zambia Meteorological Department.

Compared to the intra-year distribution of rainfall, reference evapotranspiration (ET_O) shown in Figure 2.6 is low during rainy months and high during dry months. For all zones, the lowest ET_O is in December to February (around 100 mm) when wind speed is lowest and rainfall and relative humidity are highest for the year. The highest ET_O values are in September, ranging from about 160 mm in Zone III to 200 mm in Zone IIb, with the other zones in between. During this month temperature and wind speed are highest and relative humidity is lowest for the year. Interestingly, a second peak of ET_O is seen in May, which is also confirmed by the observed open-water pan evaporation data for most of the 30 weather stations. For Zone III, relative humidity during May is lower and wind speed is higher than during the two neighboring months, which may explain the small peak of ET_O in May. This is not seen in other zones.[5]

Year-to-year variations in rainfall are generally high in zones with low rainfall and low in wetter zones towards the north of the country. Figure 2.7 gives the normalized standard deviation (i.e., coefficient of variation) of annual rainfall for the period 1976-2007. The dry Zones I and IIa1 have the highest inter-annual rainfall variability, with coefficient values of 0.180 and 0.203 respectively. Assuming that the annual rainfall amount follows a normal distribution, this implies that in Zone IIa1, for example, there is about a 30 percent probability that rainfall in any given year is 20 percent (i.e., 170 mm) higher or lower than the mean rainfall level of 820 mm shown in Figure 2.4. This indicates potential drought or flood events depending on the distribution of the rainfall deficit or the intensity of the rainfall surplus in a particular rainy season. A higher coefficient of variation for Zone IIa1 inidates this zone to have higher inter-annual rainfall variation than Zone I, despite the latter having lower average annual rainfall.

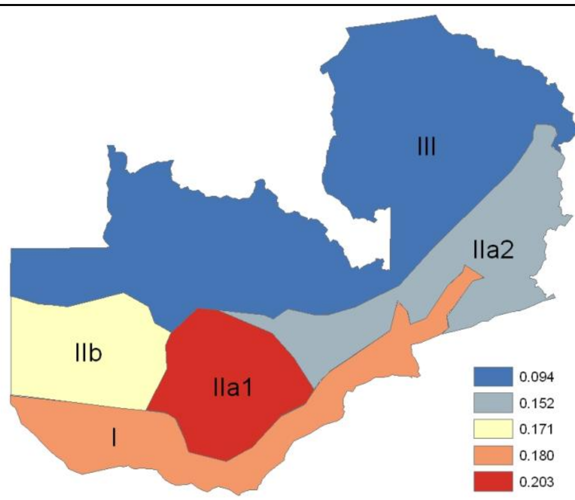
[5] A thorough explanation of the bimodal intra-year distribution of ET_O needs further analysis.

Figure 2.6: Mean monthly reference evapotranspiration in agroecological zones, 1976-2007



Source: Authors' calculations using historical rainfall data from the Zambia Meteorological Department.

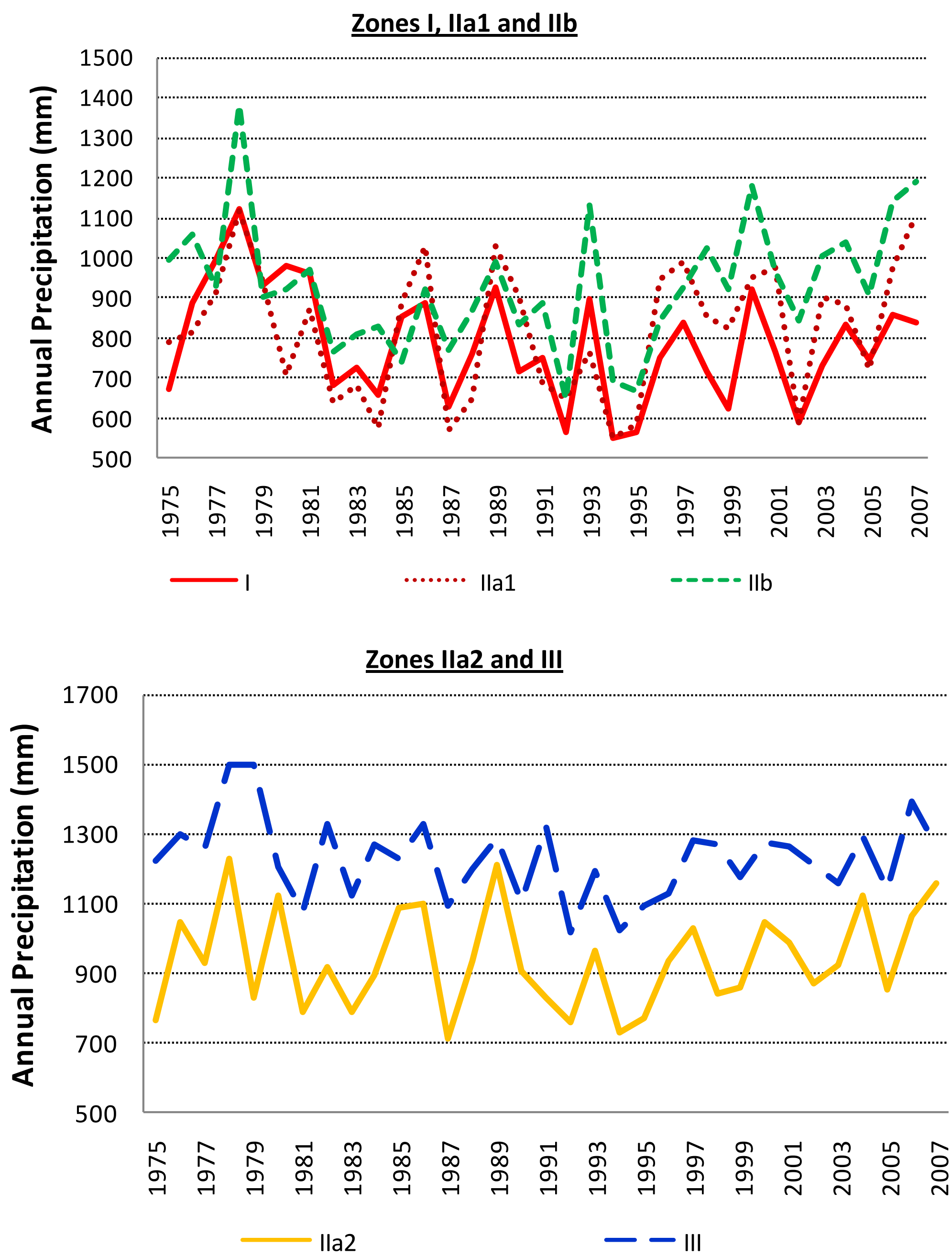
Figure 2.7: Annual precipitation coefficient of variation by agroecological zone, 1976-2007



Source: Authors' calculations using historical rainfall data from the Zambia Meteorological Department.
Notes: Standard deviation normalized by mean, indicating inter-annual variations of rainfall in an agro-ecological zone.

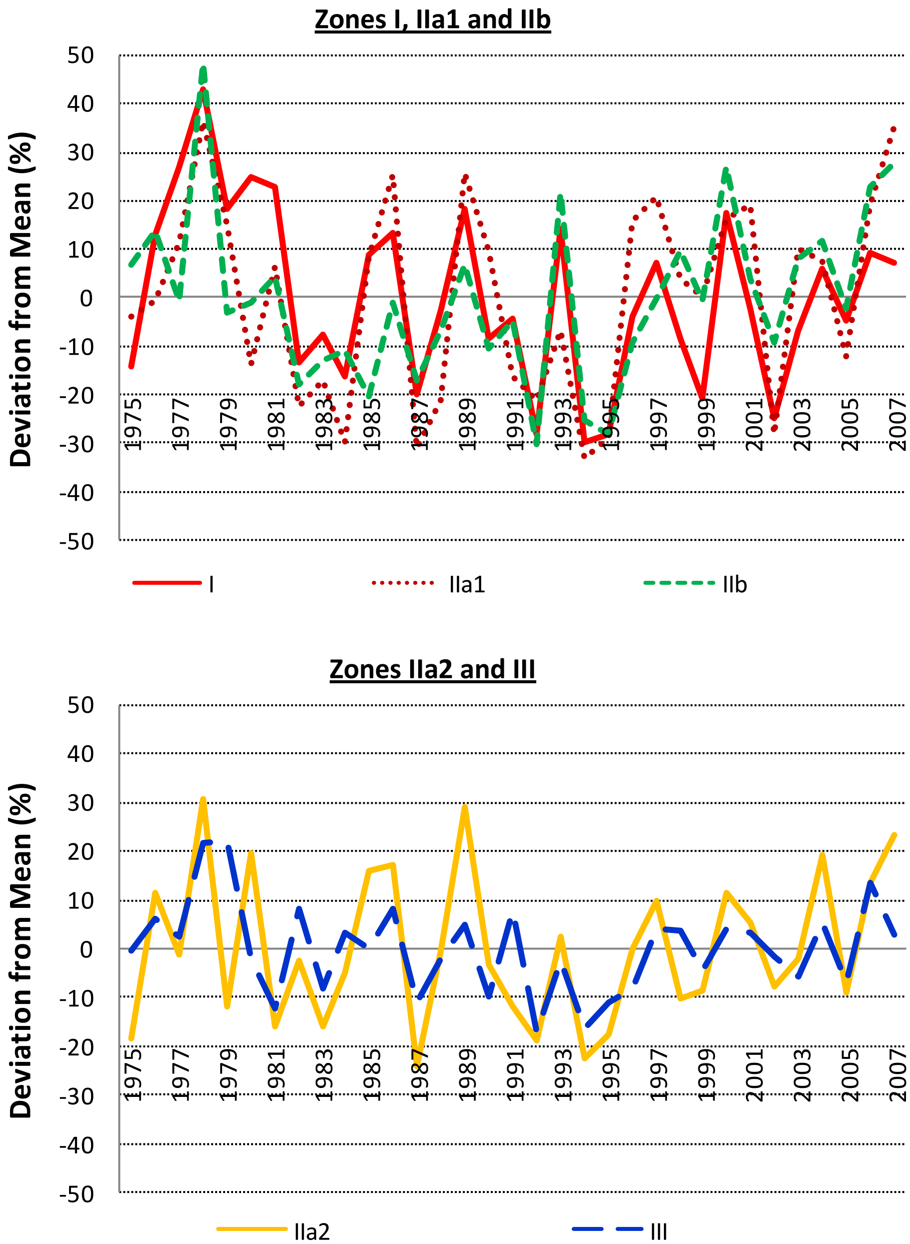
Figure 2.8 shows inter-year rainfall variations in each of the five zones, while Figure 2.9 shows the percentage deviations of annual rainfall from their means. Annual dry and wet fluctuations appear to share the same rhythm in major drought or wet years in Zones I, IIa1, IIa2 and IIb, except for Zone III. This indicates that drought events can be nationwide in some years, making the country less capable of mitigating its consequences through its own efforts. The wet Zone III shows only moderate inter-year rainfall variation, with most years lying within 10 percent of the mean and rarely falling below 1100 mm. By contrast, rainfall deviations in Zones I, IIa1 and IIb frequently exceed 20 percent of the mean, and even approach 30 percent deficits in major drought years.

Figure 2.8: Annual precipitation of agroecological zones, 1976-2007



Source: Authors' calculations using historical rainfall data from the Zambia Meteorological Department.

Figure 2.9: Annual deviation in precipitation from long-term mean for agroecological zones



Source: Authors' calculations using historical rainfall data from the Zambia Meteorological Department.

Potential evapotranspiration of maize in its growing season are shown in Figures 2.10.[6] Maize is chosen for the discussion because it is Zambia's most important annual crop. Clearly the amplitudes of inter-year potential evapotranspiration variations are much smaller than rainfall. Nevertheless, like rainfall, the variations of potential evapotranspiration are large in Zones I, IIa1 and IIb but small in Zones IIa2 and III. Even for zones with large variations, the difference in maize evapotranspiration between any two years is well within 100 mm. For Zone III, the largest difference in two years is only around 30 mm. Potential evapotranspiration of maize during the growing season in each of the zones is found to be inversely correlated with zonal rainfall. These opposite deviations of rainfall and potential evapotranspiration in the same year are particularly apparent in major drought years (1986/87, 1991/92, 1994/5 and 2004/05) and major wet years (1977/78, 1988/89, 1992/93 and 2006/07).[7] This implies that larger-than-usual amounts of water are needed by crops during years when rainfall is low. On the other hand, crop water requirements are usually below normal in years when rainfall is high, with flooding and water-logging implications.

2.3 Distribution of droughts and wet events based on drought index analysis

Droughts are complex phenomena and an index is often used to measure their severity. For agriculture, drought indices usually take into account the amount of soil water available to the crop rather than focusing only on rainfall deficits. For this study we use a Palmer Z Index (Palmer 1965; Allen 1984) as a drought severity metric, since it is a better indicator of monthly soil moisture conditions than other indices. The Palmer Z index is based on the supply-demand concept of soil water balance, taking into account more than just rainfall deficits at specific locations. It also provides a standardized measure of moisture conditions, thus allowing for comparisons across locations and time periods (Palmer 1965).

The annual drought indices discussed below are in fact a wet season (November-March) average of the monthly Palmer Z-index. This is because the wet season overlaps with the growing period of most rain-fed crops, including maize. A negative value for the Palmer-Z-index indicates dry conditions, while a positive value indicates wet conditions. Unfortunately, the monthly meteorological data used in this study do not provide sufficient information to identify floods, which usually occur over much shorter periods of time such as a few days of heavy rains (World Bank, 2008). However, the wet conditions indicated by a high positive value of the Palmer Z index might suggest possibilities of flooding. Monthly Palmer Z indices were calculated for 1975-2007 for the five agroecological zones, and were then averaged over the wet season to create annual drought indices for each zone for the 1976-2007 harvest years. As shown in Table 2.1, threshold values for the index were chosen in order to categorize the growing seasons into severe drought years (-1.5), moderate drought years (-0.5), normal years, moderately wet years (0.5) and very wet years (1.5).

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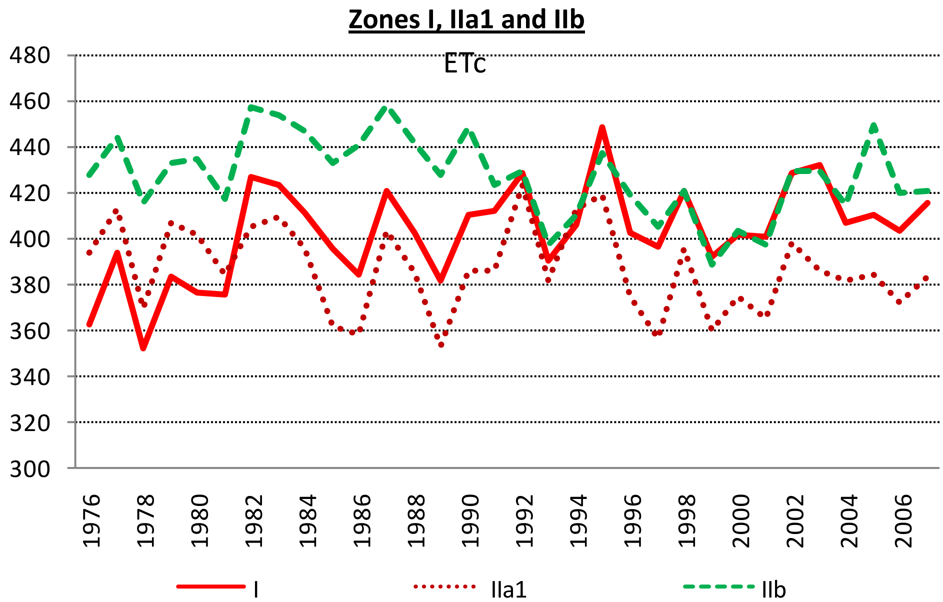
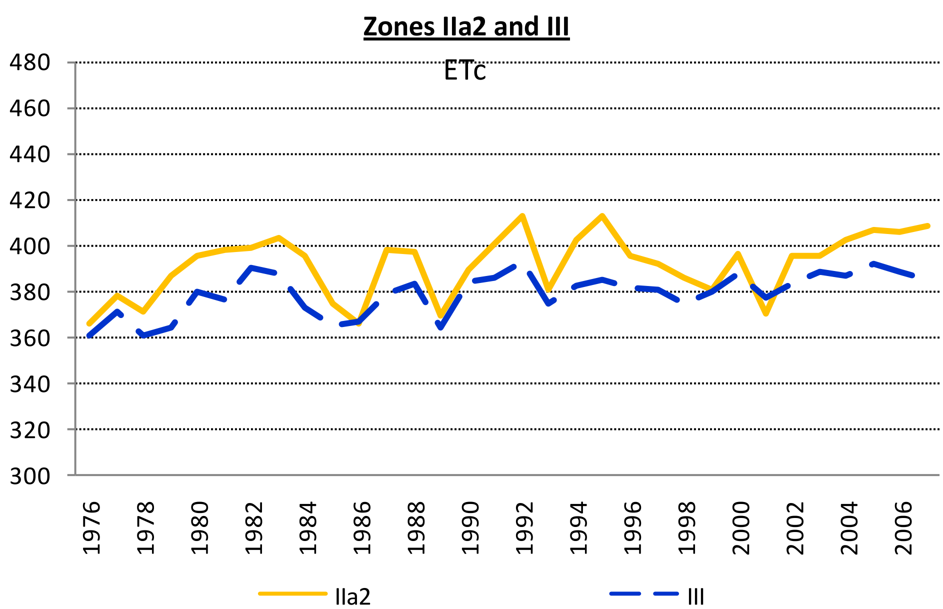
[6] See Appendix A.

[7] The harvest year is usually associated with drought/floods, despite the growing season spanning two calendar years. For example, the drought that took place during the 1991-92 season corresponds to 1992 for other data sources (e.g., national accounts). We follow this convention when the season is not identified explicitly in the text.

Figure 2.10: Growing period potential evapotranspiration of maize in agro-ecological zones, 1976-2007





Source: Results from the hydro-crop model.

Table 2.1: Number of years of simultaneous climatic event occurrences across agroecological zones, 1976-2007

Number of zones simultaneously affected	Severe drought ($Z^a \le -1.5$)	Moderate drought ($-1.5 < Z \le -0.5$)	Normal ($-0.5 < Z \le 0.5$)	Moderately wet ($0.5 < Z \le 1.5$)	Very wet ($Z > 1.5$)
5	0	1 (1994)	0	0	0
4	0	4	0	4	1 (1978: I, IIa1, IIa2, IIb)
3	1 (1992: I, IIa1, IIb)	4	6	5	0
2	2 (1995: I, IIa1; 2005: I, IIa1)	4	11	2	1 (1981: I, IIb)
1	1 (1987: IIa1)	7	10	9	4 (1979: III; 1989: IIa1; 1997: IIa1; 2004: 2b)

Note: Averaged monthly Palmer Z Index in maize growing period from November to March. The monthly Palmer Z index shows how monthly moisture conditions depart from normal, reflecting short-term drought and wetness (Palmer 1965; Alley 1984).

Apart from a drought's severity measure, its spatial extent can prove as important for agriculture. Simultaneous drought conditions over large areas can greatly reduce a country's ability to mitigate negative outcomes and provide food assistance to drought-stricken regions. Table 2.1 gives the frequencies of drought/wet events taking place simultaneously across agroecological zones. It shows that the worst drought event during 1976-2007 happened in the 1991/92 growing season, when three out of the five zones experienced a severe drought (i.e, Zones I, IIa1, IIb). Both Zones I and IIa1 had severe droughts during the 1994/95 and 2004/05 seasons, while only Zone IIa1 had a severe drought in 1986/87. These four seasons represent the major drought years in the historical rainfall data.

Moderate droughts occur more often than severe droughts and usually affect larger areas. Table 2.1 shows that all five agroecological zones had moderate droughts during the 1993/94 season. This is the only countrywide moderate drought observed in the 32-year period between 1976 and 2007. There were four other rainy seasons during 1976-2007 when four of the five zones were simultaneously affected by moderate droughts; four seasons when only three of the five zones were simultaneously affected; and four seasons when only two of the five zones were simultaneously affected. However, the situation where only one agroecological zone is under moderate drought conditions happens more frequently. There were seven seasons with moderate droughts for one of the five zones, indicating a reoccurrence interval of each 4.5 years.

'Normal' weather (i.e., a Palmer Z index between -0.5 and 0.5) never happens simultaneously in more than three of the five agroecological zones during the 32-year study period, indicating that Zambia is prone to extreme weather events. There were six seasons when normal weather simultaneously occurred in three of the five zones; eleven seasons when normal weather simultaneously happened in two zones; and ten seasons when normal weather happened in only one zone.

Moderately wet and very wet events appear to be less frequent than droughts, and they never simultaneously happened in all five zones. The indices show that there were four seasons when moderately wet conditions simultaneously occurred in four of the five zones; five seasons when moderate drought simultaneously happened in three zones, and two seasons when moderate drought simultaneously happened in two zones. The chances that only one zone is moderately wet is considerably higher (i.e., nine seasons out of a total of 32 years).

Finally, as with severe droughts, very wet conditions rarely occur simultaneously in Zambia. Only in the 1977/78 season did four zones simultaneously experience very wet conditions (i.e., Zones I, IIa1, IIa2 and IIb). Moreover, only in the 1980/81 season were two zones simultaneously affected (i.e., Zones I and IIb). Four seasons were found to have only one agroecological zone under very wet conditions during the study period.

Some conclusions can be drawn from the index statistics in Table 2.1. First, Zambia is prone to droughts and floods, with a high chance that at least one agroecological zone experiences abnormal weather events in any given year. Secondly, the central and southern regions of the country (i.e., Zones I, IIa1 and IIb) are particularly prone to both droughts and floods. By contrast Zone III has fairly stable weather conditions, with no severe droughts having taken place over the last three decades and only one season identified as very wet (i.e., 1978/79). Thirdly, it seems drought events are occurring more frequently, with almost all of the country's severe droughts taking place during the second half of the study period.

3. Modeling the biophysical impact of climate variability using a hydro-crop model

Two types of models were used to analyze economic impacts of variability and climate change. An integrated hydro-crop (HC) model was first used to predict soil water balances and crop yield responses in Zambia's five agro-ecological zones. This information was then applied into a dynamic economywide computable general equilibrium (DCGE) model, which estimated impacts on production at the subsector, zonal and national level and on household incomes and poverty. This section describes the hydro-crop model and the estimation of crop yield losses resulting from climate variability.

Quantitative information on crop yield responses to water deficiency is crucial for evaluating the economic impacts of climate variability and change on agricultural production. Climate variability's impact on agriculture is especially important in Zambia since this is the primary impact channel through which the broader economy is affected (World Bank, 2008). There are different approaches to estimating crop yields under varying weather conditions. One approach is to use process-oriented crop growth models to simulate crop growth and yields, taking into account detailed biophysical processes from the root extraction of water and nutrients to plant photosynthesis and yield formation. However, these kinds of models require extensive soil and crop information, and are typically constructed separately for different crops. Given the lack of data in Zambia, we adopt a semi-empirical approach and develop a hydro-crop model that includes two stages: the first stage is to simulate actual evapotranspiration using a soil water balance model for crop root zone similar to that recommended in Allen et al. (1998); and the second stage is to estimate crop yield responses to water deficits using an empirical crop water production model originally proposed by Jensen (1968). Together these two stages form an integrated 'hydro-crop' model that is used in this study.

The output of the hydro-crop model becomes an input into the economywide model in order to assess the economic impact of climate variability. For this study, a dynamic computable general equilibrium (DCGE) model has been developed and this model, together with the hydro-crop model, is applied to analyze economic impacts of climate variability and change. The DCGE model contains information on different sectors, factors and households in each of the five agro-ecological zones. For example, the model distinguishes between 34 different sectors, half of which are crop and livestock subsectors and the other half are industrial and service subsectors. Production in each agricultural subsector was disaggregated across zones using district-level data provided by the Ministry of Agriculture, Food and Fisheries. We also separate small/large-scale and rural/urban agricultural production. So the model captures differences in cropping and livestock patterns driven by agro-ecological conditions and by farm land endowments. This disaggregation of production allows the DCGE model to capture how climate conditions vary across zones, and how climate affects crops differently according to their agronomic characteristics. The economywide model's characteristics and simulations are described in detail in Section 4.

3.1 The hydro-crop (HC) model

The soil water balance module of hydro-crop model regards crop root zone as a bucket with water flowing in through rainfall, and irrigation if applicable, and water leaking away as ET, runoff and deep percolation. The first step in the soil water balance is to estimate crop water requirements, which are normally expressed by the rate of potential evapotranspiration (ET). The United Nation's Food and Agriculture Organization (FAO) has developed a practical procedure to estimating crop water requirements (Allen et al., 1998) which has become a widely accepted standard. Owing to the difficulty of obtaining readily available and accurate field measurements, the estimation of crop water requirements are derived from estimating crop evapotranspiration according to reference crop and climatic conditions. The water requirements of a given crop are derived through a crop coefficient that integrates the combined effects of crop transpiration and soil evaporation into a single crop coefficient.

The potential ET for a particular crop is estimated using potential ET of a reference crop, usually alfalfa, and a calibrated crop coefficient which converts the reference ET to potential ET of the crop, under given climatic conditions. With rainfall and potential ET,the soil water balance model takes into account the water flowing into the crop's root zone from precipitation (assuming no irrigation) and the water leaving the crop's root zone due to evapotranspiration, surface runoff and deep percolation. It then balances these flows using the crop's root zone available water capacity (AWC) as storage. If the soil water content is above a threshold level of AWC then actual evapotranspiration takes place at the potential rate. But if it is not, then actual evapotranspiration is stressed by soil moisture. Surface runoff and deep percolation occur if the estimated end-of-period soil water content exceeds AWC.Details of the soil water balance model and the crop water production model are given in Appendices A and B.

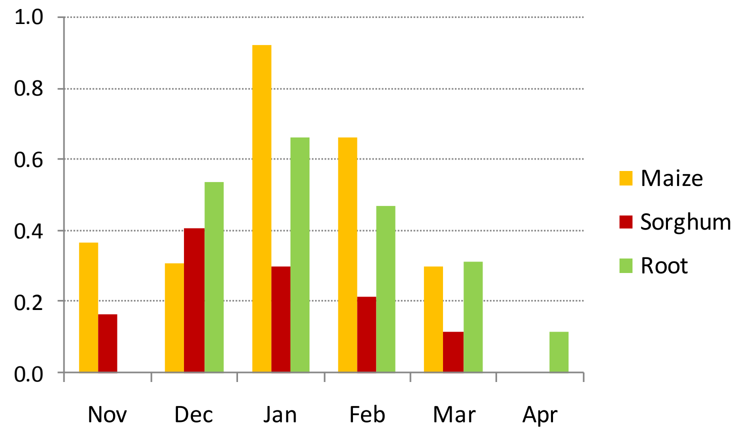
There is a rich literature on crop yield responses to water deficits (e.g. Jensen, 1968; Doorenbos and Kassam, 1979). However, the choice of which crop water production models to use for economic evaluations is usually constrained by the complex nature of these models and the availability of model parameters. Thus, simpler estimation models, such as the FAO linear yield response model (Doorenbos and Kassam, 1979) and Jensen's model (Jensen, 1968), are usually preferred to more complex models.

The FAO model is a practical approach to measuring yield responses to water supply. It is relatively simple; requires commonly available climatic, water, soil and crop data; and is applied widely with acceptable levels of accuracy.[8] However, comparing observed yields and FAO model simulations for Zambia suggests that crop losses in the country are especially sensitive to seasonal water deficits. Therefore, it is not appropriate to use the FAO model, which uses relative evapotranspiration for the entire growing season, and thus cannot capture monthly climate variations and crop yield sensitivities in Zambia. Instead we used the Jensen crop water production model[9]. Crop water sensitivity index values were estimated using OLS regression and based on FAO yield response factors for each growing stage (FAO, 1979). These were then mapped to each month in crops' growing periods using the cumulative

[8] Equation 2.8 in Appendix A.
[9] Equation 2.9 in Appendix A.

sensitivity index method (Tsakiris, 1982; Kipkorir, 2002). Figure 3.1 shows the value of the monthly crop water sensitivity index for maize, sorghum and root crops.

Figure 3.1: Crop water sensitivity index in Jensen crop water production function for maize, sorghum and root crops



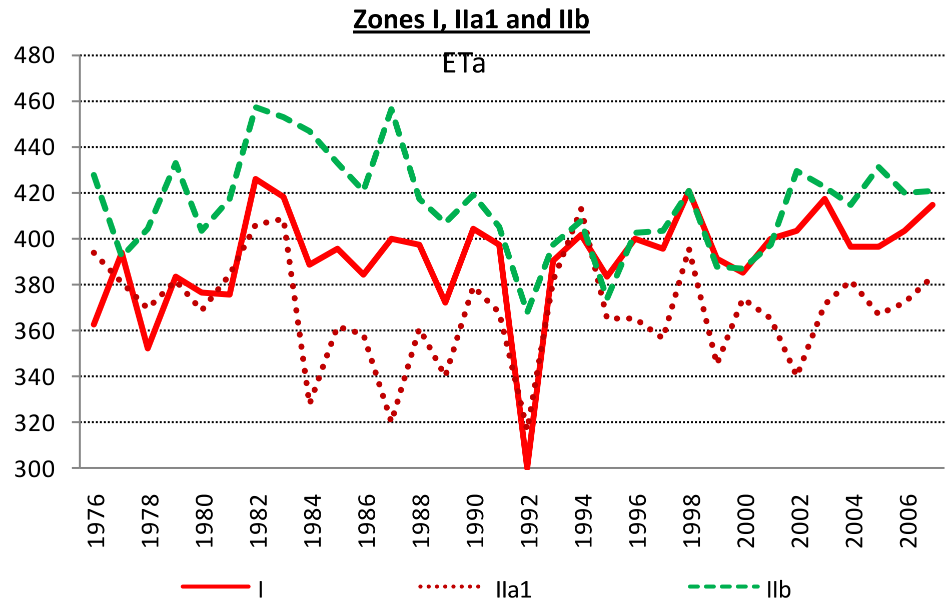
3.2 Impact of climate variability on crop yields – HC model results

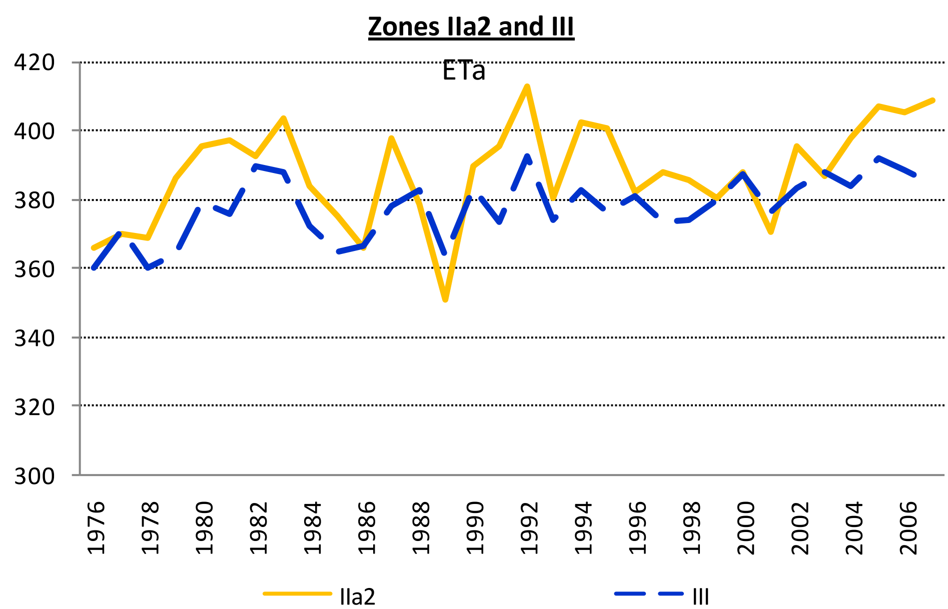
Figure 3.2 shows the simulated actual evapotranspiration for the maize growing season in the five agroecological zones. Modulated by crop water requirements and soil moisture contents, actual evapotranspiration in the three drier zones (i.e., Zones I, IIa1 and IIb) show rising and downward patterns similar to the rainfall patterns in Figure 2.8. This is because the limiting factor in these zones is the available soil water content. However, actual evapotranspiration in the wetter zones (i.e., Zones IIa2 and III) follow the potential evapotranspiration patterns in Figure 2.10, because soil water content does not stress evapotranspiration in these zones (i.e., it is controlled by atmospheric water demand).

Simulated relative maize yields for 1976-2007 are shown in Figures 3.3 for the five agroecological zones. Relative yields are defined as the ratio of the simulated actual yield to the maximum yield achievable without any water stress. Maize is again chosen as an illustrative example because it is Zambia's major crop. However, relative yields for other crops follow similar patterns to maize.

For Zones I and IIa1, the worst maize yield reduction occurred in the 1991/92 season when estimated relative yield losses were 77 percent and 65 percent, respectively, of normal yields. While Zone IIb had a 40 percent yield loss in 1991/92, its worst season was in 1994/95 when there was a 54 percent yield loss for maize. Considerable yield losses were also found in other seasons for the drier Zones I, IIa1 and IIb. These include 1994/95 for Zones I, IIa1 and IIb; 1976/77 for Zones IIa1 and IIb; and 1983/84, 1986/87 and 2001/02 for Zone IIa1. The relative yield reductions during these seasons range from 30 to 50 percent. Figure 3.3 also shows that there were no major yield losses caused by droughts in Zones IIa2 and III. For Zone III, in particular, its highest relative yield reduction was 14 percent in 1991/92. For Zone IIa2, the highest relative yield loss was 20 percent, occurring in 1988/89. In general, Zone IIa2 is much less drought-prone than Zones I, IIa1 and IIb, and drought-induced crop yield losses in zone III are rare.

Figure 3.2: Growing period actual evapotranspiration of maize in agroecological zones, 1976-2007





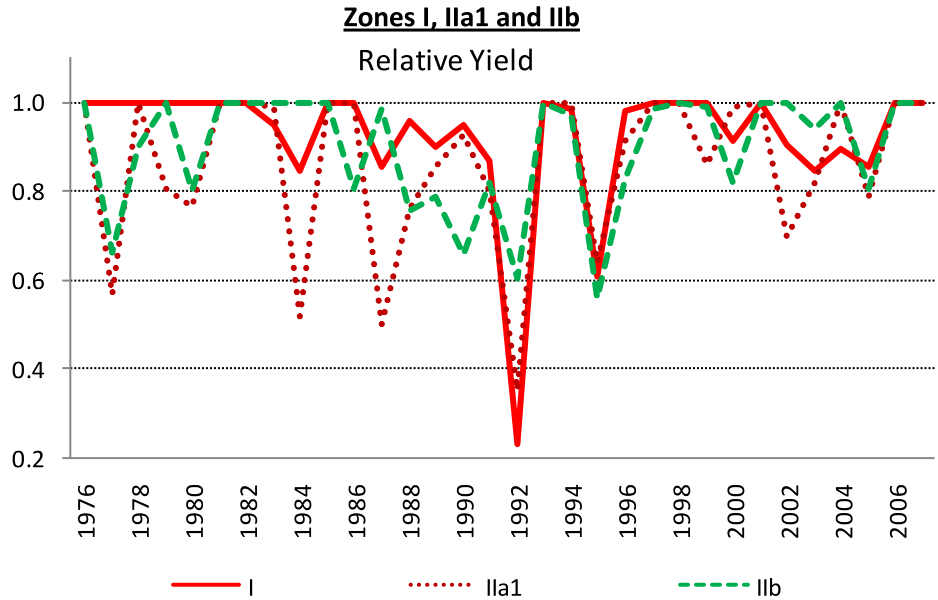
Source: Results from the hydro-crop model.

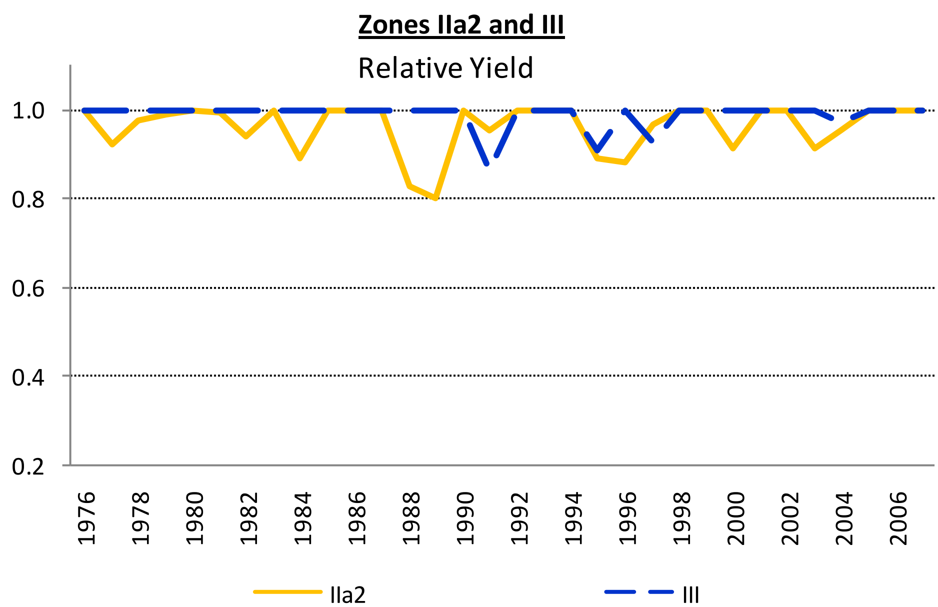
Table 3.1 provides information to help in understanding the nature and consequences of droughts/wet events. The table shows the ranges of growing season rainfall; relative yield losses; and the frequency of weather events. It also shows the crop water requirement satisfactory index (WRSI), which is the ratio of actual to potential evapotranspiration during the growing season (Verdin et al., 2005). Each of these indicators is separated across agroecological zones and event categories. For example, the range of growing season rainfall in Zone I for all severe drought years is 405-499mm.

The table indicates that for the three drier zones (i.e., Zones I, IIa1 and 11b) there were only 7 or 8 years out of 32 years (i.e., 1976-2007) that are identified as normal years in which the amount of rainfall in growing seasons is in the normal range. This indicates that there is a 75 to 80 percent chance in any given year that there is a drought or too much rain in these three zones. Moreover, over the 32 years, three severe droughts occurred in Zone I, four in Zone IIa1, and one in Zone IIb, and there was no severe drought in the other less dry zones (i.e., Zones IIa2 and IIb). During severe drought years, Zones I and IIa1 experienced the largest reductions in relative yields (i.e., 14-77 and 21-65 percent respectively). The average relative water deficit (i.e., 100 - WRSI) is usually not as high as relative yield losses during severe droughts. Rather it was abnormally low rainfall during critical growing stages that caused substantial yield losses. Ultimately, Table 3.1 illustrates again that Zones I, IIa1 and IIb are drought-prone, while major drought damage is rare in Zones IIa2 and III. Despite being the wettest zone in the country, very wet weather event is also rare in Zone III, with only one occurrence during the study period.

It should be noted that the models used in this study are for drought impact assessments, and therefore crop yield losses resulting from floods or water-logging are not assessed. This is primarily because floods are usually highly localized and with short durations. Hence, any damage assessment requires high-resolution data that is not readily available in Zambia. However, drought damage is more important than flood damage for Zambian agriculture (World Bank, 2008). Moreover, the analysis of wet events in Tables 2.1 and 3.1 provides some measurement of possible flood events, and shows that crop yield losses can also occur in wet years due to the uneven distribution of seasonal rainfall.

Figure 3.3: Maize relative yield in agroecological zones, 1976-2007





Source: Results from the hydro-crop model.

Table 3.1: Palmer Z drought index-based weather classification and the ranges of derived climatic and agronomic statistics, 1976-2007

		Severe drought year ($Z^a \le -1.5$)	Moderate drought year ($-1.5 < Z \le -0.5$)	Normal year ($-0.5 < Z \le 0.5$)	Moderately wet year ($0.5 < Z \le 1.5$)	Very wet year ($Z > 1.5$)
Zone I	Growing period rainfall (mm)	405-499	481-624	632-751	746-902	971-1031
	Maize WRSI[b] (%)	70-96	94-100	96-100	97-100	100
	Maize yield loss[c] (%)	14-77	1-15	0-8	0-10	0
	Frequency[d]	3	8	8	11	2
Zone IIa1	Growing period rainfall (mm)	401-506	505-623	711-781	761-887	961-1008
	Maize WRSI (%)	75-95	83-100	94-100	92-100	96-100
	Maize yield loss (%)	21-65	0-48	7-19	1-23	0-14
	Frequency	4	9	7	9	3
Zone IIa2	Growing period rainfall (mm)	-	635-781	765-954	910-1058	1113[e]
	Maize WRSI (%)	-	97-100	95-100	95-100	99
	Maize yield loss (%)	-	1-11	0-17	0-20	2
	Frequency	-	11	10	10	1
Zone IIb	Growing period rainfall (mm)	585	578-766	765-858	927-1085	1079-1125
	Maize WRSI (%)	86	86-100	88-100	95-100	97-100
	Maize yield loss (%)	40	0-44	1-34	0-21	0-10
	Frequency	1	13	7	8	3
Zone III	Growing period rainfall (mm)	-	875-987	960-1158	1136-1314	1290
	Maize WRSI (%)	-	98-100	97-100	100-100	100
	Maize yield loss (%)	-	0-9	0-13	0-0	0
	Frequency	-	7	18	6	1

Notes: (a) Average monthly Palmer Z Index in maize growing period (November-March). Palmer Z index shows how monthly moisture departs from normal conditions and reflects short-term drought or wetness (Palmer 1965; Alley 1984); (b) 'WRSI' is water requirement satisfactory index and is the ratio of total actual to total potential crop evapotranspiration (see Section 2.3); (c) Percentage maize yield loss estimated from hydrological model; (d) Number of years of occurrences during 1976-2007. Using the monthly averaged Palmer Z index and the -1.5 threshold did not identify year 1992 as a severe drought year in Zone I where estimated maize yield reduction in this study (about 77%) was the severest among all five agro-ecological zones, although the index successfully identified the other severe drought years, 1995 and 2005 for zone I. The reason is that there was only 22 mm of rainfall fallen in February, 1992, which is about 13% of average rainfall in this month. The extreme rainfall shortage occurring in critical maize growing stage resulted in dramatic yield loss in 1992. As a fix, we moved 1992 from the moderate drought category to severe drought for zone I. (e) Only one very wet event was found in zone IIa2 during the 1996-2007 period so no need is reported. The same is true for severe drought in Zone IIb and very wet event in Zone III.

4. Climate variability and economic growth – combining the HC and DCGE models

The previous sections examined historical trends in climate variability across Zambia's five major agroecological zones (Section 2) and estimated their annual impact on crop yields over the last three decades using a hydro-crop model (Section 3). Drawing on the hydro-crop model results and climate variability data, this section assesses the potential impact of *future* climate variability on economic growth and household incomes and poverty using the dynamic CGE model developed for this study.

4.1 The dynamic computable general equilibrium (DCGE) model

Climate variability not only affects crop yields, harvested areas, and agricultural production, but also has implications for the entire economy. Moreover, spatial variation in rainfall patterns means that such effects vary across sub-national regions. We therefore developed an economywide model with five agroecological zones.[10] The model contains detailed information on production, consumption and trade. There are totally 34 different production sectors, half of which are agricultural crops and livestock. These sectors are defined for the five agroecological zones as five representative rural farm groups, together with large-scale and urban farm groups. The technologies of these representative farm groups (together with the nonagricultural production functions) are calibrated using district level production data from the Crop Forecasting Surveys (CFS) and the 2004 Living Conditions Monitoring Survey (LCMS4). Each farm group can change cropping and livestock patterns and engage more or less intensively in nonfarm activities. Laborers can also migrate to urban centers and nonagricultural jobs (both are modeled explicitly). This model setup therefore captures some autonomous adaptation to climate change. We do, however, limit the extent to which representative producers adjust cropping patterns in response to short-term climate variability. We assume that land allocations are determined at the start of the season, and, once planted, farmers cannot reallocate land to different crops during the growing season (i.e., land allocations in short-run are exogenous). This assumption is appropriate since farmers typically cannot predict and respond to climate variation once land in planted. They can, however, reallocate mobile resources, such as labor, and influence the level of production.

While substitution between factors (labor, land and capital) depends on relative costs, the model distinguishes between self-employed agricultural workers; unskilled workers (working in both agriculture and non-agriculture) and skilled workers (in non-agriculture only). Information on employment and wages is from LCMS4, while labor supplies expand over time exogenously according to demographic projections. Capital is immobile across sectors, and, after accounting for annual depreciation, is supplemented by past investments allocated according sectors' relative profitability. This is the 'recursive' dynamic feature of the DCGE model. Total factor inputs are then combined with intermediate inputs (e.g., fertilizer and fuels) to produce a total level of output. These sector-specific production technologies are taken from a 2006 Zambian social accounting matrix (SAM). Producers in each sector/region decide how much output to supply to national domestic and foreign markets based

[10] The economywide model used is a recursive dynamic computable general equilibrium (DCGE) model developed by Thurlow (2005). Appendix C presents the equations and parameters of the DCGE model.

on relative prices. Since Zambia is a small country, we assume that world prices are fixed, but are influenced by changes in the real exchange rate, which adjusts to maintain the current account balance.

In order to capture how different households are affected by climate variability and change, the model includes 15 representative household groups by zones, rural and urban, and by the size of farms (small rural, large-scale rural and urban farmer households). Income and expenditure patterns vary across the 15 household groups. This is important for distributional change since incomes generated during farm/nonfarm production accrue to different households depending on their location and factor endowments. Households in the model receive factors' incomes and then pay taxes, save and make transfers to other households. Remaining incomes are used to consume goods and services, which can either be purchased locally or imported depending on relative prices. Taxes are collected by the government, which also consumes goods and services, while pooled savings are used to finance investment spending. Total demand interacts with production and trade (i.e., supply) to determine prices in the model. This full specification of supply/demand for commodities and factors using production and utility functions is the 'general equilibrium' feature of the DCGE model. Finally, in order to retain as much information as possible on households' income and expenditure patterns, the DCGE model is linked to a microsimulation module based on LCMS4. Changes in consumption for each representative household in the DCGE model are used to adjust the level of commodity expenditure of corresponding households in LCMS4. Consumption levels are then recalculated in the survey, and standard poverty measures are re-estimated.

The model distinguishes domestic markets from trade with rest of world for the most important trading commodities. However, international prices can affect domestic supply and demand through imperfect substitution with domestic supply as well as through the real exchange effect. The linkages among different agricultural subsectors and between agricultural and nonagricultural sectors are fully captured through income generation and household expenditures and through use of intermediate inputs. Because such model setup, the economywide impacts of climate variability in Zambia can be captured. Detailed description of data applied to represent the Zambian economy in 2006, the macroeconomic and sectoral structure of the production, is taken from national accounts and crop production data, while information on household incomes and expenditures is drawn from 2004 Living Conditions Monitoring Survey. Note that the agricultural season used for the calibrated base year of the model is 2005/06. Appendix B provides a detailed description of

4.2 Combining the HC and DCGE models and designing scenarios of alternative rainfall sequences

The DCGE model is used to simulation of 10 years' period of climate variability between 2006 and 2016 and to assess the economic impact of such variability in this period. It is impossible to accurately predict Zambia's future annual rainfall pattern. It is, however, possible to identify a range of possible patterns using historical data. Many methods have been developed to simulate the future potential rainfall patterns. In our study we use an 'index sequential method' (Prairie et al, 2006). Given 32 years of historical rainfall data for the period 1976-2007, we can draw 32 different ten-year rainfall sequences (i.e., 32 different starting years for each ten-year consecutive sequence). This method preserves the original inter-annual correlations inherited in the observed climate data. We include all 30 of the possible sequences in our analysis and thus capture the full distribution of past climate variability. This approach has the advantage of greatly reducing the number of possible rainfall scenarios, while also capturing any interdependencies between rainfall patterns across consecutive years.

Thus, the starting point (or the base-year) of the DCGE model is 2006, which is the most recent year for which all of the necessary data is available and all model's parameters thus are calibrated to this year.We first apply the DCGE model to a scenario with 'normal' rainfall for each of the ten years between 2006 and 2016 (i.e., during the simulated 10 years there are no adverse effects from climate variability on the economy). Because of this insulation from climate variability, crop yields are assumed to be stable. Moreover, the level of yields and the allocation of land are assumed to grow steadily according to estimated yield potentials drawn from field trials and historical trends in land expansion (see Thurlow et al., 2008). We call this scenario 'normal rainfall without climate variability' (or normal rainfall in short). We then develop 30 scenarios each of which has a period of 10 years. These scenarios are developed to simulate the economic impact of different rainfall patterns discussed above (i.e., using the index sequential method to reproduce various historical rainfall patterns for the next 10 years). The link between various rainfall patterns and the economywide model is through the imposition of crop yield shocks in the model. These yield shocks are consistent with the hydro-crop model results discussed in the previous section. This is done by crops for each of the five agroecological zones and is repeated for all 30 ten-year rainfall sequences. As rainfall patterns are unpredictable for farmers and droughts often occur after planting, farmers usually are unable to change their crop land allocation to avoid yield loss in response to drought. Accordingly, in the model we assume that land allocation within each year is fixed by crop. Given that more than 80 percent of rain-fed crop areas are for maize, and drought-resistant crops, such as cassava and sorghum, have significant spatial patterns, this assumption seems to be more reasonable than a flexible land allocation assumption that is commonly used in many other CGE models. While farmers are unable to reallocate land into other crops, they still can decide to reallocate other inputs, including labor, capital and intermediate inputs in response to climate variability. For example, labor and capital may switch into other agricultural and nonagricultural activities, such as participating in some off-farm activities as workers, in response to changes in agricultural prices and nonagricultural employment opportunities resulting from the drought.

Apart from imposing the yield shocks drawn from the crop model, we also account for other transmission channels through which *extreme* rainfall variation affects the agricultural sector and the rest of the economy. These additional non-yield impacts only occur when there is a severe drought or flood event.[11] The various impact channels are summarized in Table 4.1.

[11] Major drought events are defined for a particular agro-climatic zone as being years in which the water response index is two standard deviations or more below the mean for the period of 30 years (1977-2007). For Zone 2a1 this occurred in the following seasons: 1983/84, 1986/87, 1991/92, 1994/95 and 2001/02. Due to a lack of data to support the modeling of floods, only the 2007/08 season is identified as a major flood event.

Table 4.1: Climate **variability and severe drought/flood event impact channels assumed in the economywide model**

Impact channel	Affected sectors	Description of impact
All 10 years in each of the 30 sequences		
Crop yields	Rainfed crops	Level of yield reduced based on the crops' WRSI
Years with severe drought events that reflect rainfall patterns in 1983/84, 1986/87, 1991/92, 1994/95 and 2001/02		
Crop area expansion	Rainfed 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 sectors	Livestock stocks decline in the drought year and the growth in these stocks gradually returns to normal year rates with diminishing lagged effects for two subsequent years
Physical capital accumulation	All sectors	Capital depreciation rates are increased in the drought year and gradually return to normal year levels with diminishing lagged effects for two subsequent years
Major flood year (2006/07)		
Agricultural land expansion	Crop sectors	Land area under cultivation declines in the flood year and only returns to pre-flood levels in the immediate post-flood year

Note: 'WRSI' is water response satisfactory index (see Section 2.3). Details of each impact channel are provided in Appendix A.

Climate variability can also affect the harvested crop areas. Accordingly, compared to the 'Normal Scenario', the harvested areas for drought-affected crops are reduced in the severe drought years and then are slowly recovered over the subsequent two years. This reflects a post-drought recovery period. Similarly, cultivated land area also declines during a major flood event, which reflects the situation observed in reality (World Bank, 2008). Stocks and productivity of livestock production are also affected by a severe drought.[12] The recovery of livestock stock is assumed to take time (about two years) and after that the growth rate of livestock stocks returns to a normal year growth rate. In other words, there is a lagged but diminishing effect on livestock stocks and productivity in the second and third years following a severe drought or flood. Severe drought is also assumed to affect other physical capital through a higher than normal depreciation rate. This reflects a deterioration or greater underutilization of capital stocks. As with livestock stocks, there is a lagged effect on the recovery of the capital depreciation rate following a severe drought or flood, with the depreciation rate returning to its normal year levels over a two-year period. Thus, while crop yield losses are the primary impact channel, the economywide model also captures numerous other possible channels through which climate variability and extreme drought/flood events affect production and productivity of both agricultural and nonagricultural sectors.

4.3 Economywide impacts of climate variability – DCGE model results

<u>Climate variability will cost Zambia US$4.3 billion in foregone GDP over ten years</u>

The first scenario of the economywide model simulates a normal rainfall situation over a ten–year period (2006-2016). 'Normal rainfall' is consistent with column 3 in Table 3.1 (labeled 'normal seasons'). Without <u>climate</u> variability in this scenario, Zambia's GDP grows at 6.7 percent per year between 2007 and 2016.[13] This result is shown as the 'normal sequence' line in Figure 4.1, with national GDP rising from US$10.2 billion in 2006 to $US19.6 billion by 2016. Growth by sectors is reported in Table 4.2, together with the contribution of agricultural, industrial, and services sectors to the economy in the beginning and ending years (i.e., 2006 and 2016). Table 4.2 also reports the model's results for poverty reduction. As shown in the table, the nonagricultural sectors grow more rapidly than the agricultural sector, which causes the share of agriculture in the national economy to decline from 20.5 percent in 2006 to 18.6 percent by 2016. Although 6.7 percent of annual growth rate is impressive, the extremely high poverty rate in 2006 means that the country is still unable to meet the first MGD goal of halving 1992's poverty rate by 2015.[14]

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[12] This severity of a drought is measured using the water response index for maize in each region.

[13] Under the normal rainfall scenario, both agricultural and nonagricultural sectors grow steadily in 2006-2016. Growth in crop yield and livestock productivity is according to their potentials defined by Zambia's Agricultural Research Institute (see Thurlow et al. 2008), while growth in the nonagricultural sector is based on the continuous trend of rapid growth experienced in the last five years (2004-2008).

[14] Zambia's national poverty rate was 70 percent in 1991. Poverty reduction in Zambia was slow during the 1990s due to a series of macroeconomic reforms and external shocks that imposed significant adjustment costs on households, especially in urban areas (Thurlow and Wobst, 2006). Rural poverty did decline towards the end of the 1990s due mainly to a rapid expansion of export agriculture in some parts of the country. Since 2000, there was a large expansion of mining and other industries, which are typically less poverty-reducing than other sources of

Table 4.2: Growth and poverty outcomes under the Normal Rainfall scenario, 2006-2016

	Average annual growth rate, 2006-2016 (%)	Share of total GDP (%)	
		2006	2016
Gross domestic product (GDP)	6.7	100.0	100.0
Agriculture	5.7	20.5	18.6
Mining	5.9	10.1	9.4
Manufacturing	7.3	12.1	12.8
Other industries	8.5	8.7	10.3
Services	6.7	48.6	48.9
	Share of total population, 2006 (%)	Poverty headcount (%)	
		2006	2016
Poverty headcount	100.0	67.9	52.2
Rural	60.9	77.6	63.0
Urban	39.1	52.8	35.4

Source: Results from the Zambian economywide model.

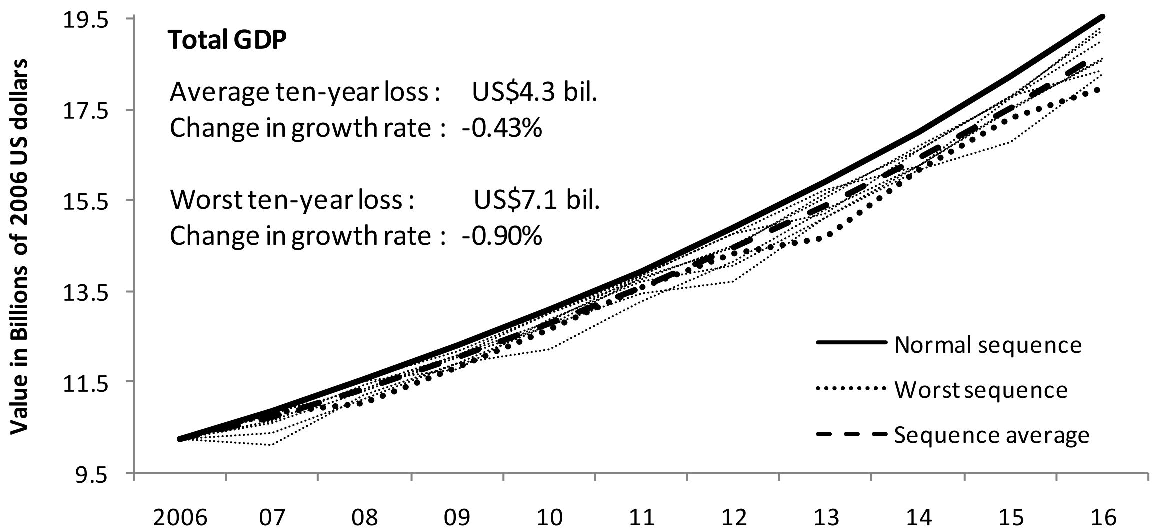
We then simulate 30 different rainfall patterns derived from the historical rainfall data using the index sequential method described in Section 3.2. Obviously, climate variability is expected to reduce the growth in GDP through the various impact channels discussed above. The extent of GDP reduction varies across different rainfall scenarios, which reflect all possible ten-year sequential patterns drawn from historical rainfall data. To better assess the potential losses in GDP due to climate variability, it is not necessary to display all the result from these 30 scenarios. Instead, we report the 'mean' results averaged from the results of 30 different scenarios, together with the results from the 'worst rainfall' sequence. We define the 'worst rainfall' sequence later in this section.

The mean GDP level averaged from all of the 30 rainfall sequences is labeled 'Sequence Average' in Figure 4.1.[15] By taking into account all possible rainfall patterns observed in the history of the country in the period of 10 years, climate variability may reduce Zambia's GDP by US$0.8 billion by the end of the ten-year period in 2016 (measured in 2006 prices). The size of Zambia's economy is therefore four percent smaller by 2016 than it would have been in the same year without climate variability. The accumulated GDP losses due to the climate variability over the ten-year period (2007-2016) reach US$4.3 billion. This is equivalent to lowering Zambia's annual GDP growth by 0.4 percentage points each year between 2007 and 2016.

growth (Breisinger and Thurlow, 2008; Thurlow and Wobst, 2006). Accordingly, Zambia's poverty-growth elasticity is considerably lower than in other African countries (Diao et al., 2007).

[15] To simplify the charts in the figure, we did not display the level of GDP under all 30 rainfall sequences and only report the mean GDP of these 30 scenarios, GDP under the worst rainfall scenario and a few of the other sequences' results served as an illustration.

Figure 4.1: Loss in total GDP due to climate variability, 2007-2016



Source: Results from the Zambian economywide model.
Note: Ten-year losses are the cumulative losses for the whole 2007-2016 period.

We identify the worst rainfall sequence according two pieces of information: the value of annual precipitation coefficient of variation (CV) and the number of severe drought events, both for a period of 10 years. The worst rainfall sequence of ten years has the highest value of CV and maximum number of severe droughts event, which reflects in the historical rainfall patterns of 1986-1995. Table 4.3 summarizes the rainfall patterns of this period and shows that the three most severe drought events all occurred during this sequence (see also Tables 2.1 and 3.1 for further details).

The economywide model simulation shows that if the rainfall patterns over Zambia's next ten years were to replicate this worst rainfall sequence then the accumulated total losses in GDP due to the more frequent severe droughts would be US$7.1 billion over the ten-year period. This is almost twice as large as the mean accumulated losses averaged from all possible rainfall patterns discussed above. This is equivalent to reducing Zambia's annual GDP growth by 0.9 percentage points each year. Moreover, the Zambian economy would be 8.1 percent smaller by 2016 than it would have been under a normal rainfall sequence. In other words, total GDP in 2016 would be US$1.6 billion below what it would have been without climate variability.

Table 4.3. Rainfall patterns in the worst rainfall sequence, 1985/86 – 1994/95

Zone			1985/86	1986/87	1987/88	1988/89	1989/90	1990/91	1991/92	1992/93	1993/94	1994/95	# severe droughts	# severe wet events
Zone I	Growing period rainfall (mm)	Total	807	547	739	850	758	607	561	797	648	430		
		Monthly min.	131	86	118	135	163	117	22	174	123	89		
		Monthly max.	243	136	234	328	249	146	206	262	173	123		
	Event occurrences		modest wet	severe drought	normal	modest wet	normal	modest drought	severe drought	modest wet	modest drought	severe drought	3	0
Zone IIa1	Growing period rainfall (mm)	Total	867	583	622	981	832	655	482	785	553	414		
		Monthly min.	155	58	140	132	132	126	33	134	123	83		
		Monthly max.	240	181	175	416	374	180	117	235	158	129		
	Event occurrences		modest wet	severe drought	modest drought	severe wet	normal	modest drought	severe drought	normal	modest drought	severe drought	3	1
Zone IIa2	Growing period rainfall (mm)	Total	1,095	794	877	1,014	1,001	735	670	997	712	669		
		Monthly min.	206	124	129	134	222	136	56	215	118	131		
		Monthly max.	297	230	268	353	288	256	173	257	236	215		
	Event occurrences		modest wet	modest drought	normal	modest wet	modest wet	modest drought	modest drought	modest wet	modest drought	modest drought	0	0
Zone IIb	Growing period rainfall (mm)	Total	827	695	814	975	747	811	601	1,094	722	622		
		Monthly min.	117	147	145	206	170	175	88	146	155	95		
		Monthly max.	226	162	228	289	253	246	190	346	275	263		
	Event occurrences		modest drought	modest drought	modest drought	modest wet	modest drought	normal	severe drought	modest wet	modest drought	modest drought	1	0
Zone III	Growing period rainfall (mm)	Total	1,210	1,055	1,125	1,140	1,112	1,147	936	1,146	987	963		
		Monthly min.	220	231	221	186	231	203	164	213	153	193		
		Monthly max.	268	241	274	281	261	381	247	299	255	265		
	Event occurrences		modest wet	normal	normal	normal	normal	normal	modest drought	normal	modest drought	modest drought	0	0

Note: Average monthly minimum rainfall is for the December to February period (peak growing period).

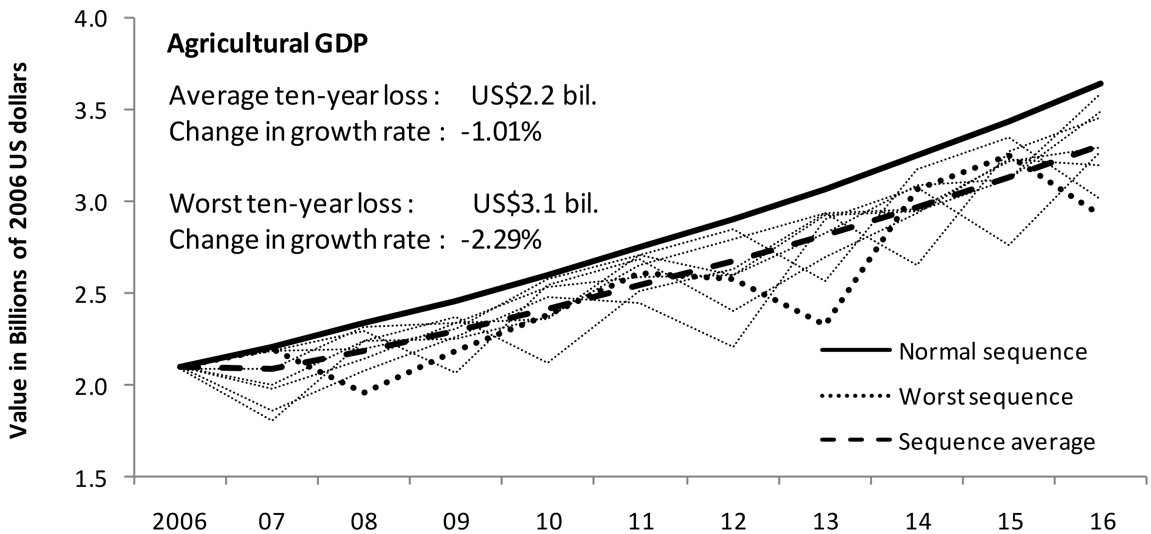
Climate variability therefore has a profound effect on economic growth in Zambia, and the losses associated with some of the worst rainfall sequences in Zambia's history are substantial. As the losses in the economy associated with the climate variability are assessed based on historical rainfall data, it is possible for us to apply the model results to the past GDP performance observed during 1977-2007. That is to say, if climate variability had not caused GDP growth to fall by 0.4 percentage point annually in 1977-2007, then Zambia's economy, measured by GDP, would have been US$1.5 billion higher now (i.e., in 2006 and in 2006 prices) than it was actually was. This is equivalent to 12.8 percent more than was actually observed in 2006. In other words, on average, Zambia lost 0.4 percent of growth annually between 1977 and 2007 due to climate variability, and the accumulated cost for this period was US$13.8 billion (in 2006 prices). Thus, while Zambia has indeed undergone several decades of unsuccessful policies and substantial structural reforms, and has suffered a number of large external shocks, all resulting in huge economic cost to the growth, climate variability has indeed contributed significantly to the country's poor economic performance and lowered economic growth, even over the last decade when development has proven more successful.

Climate variability lowers agricultural growth by one percentage point each year

As expected climate variability has a much larger negative impact on agricultural performance than on overall economic growth. Figure 4.2 shows the impact of climate variability on agricultural GDP, which supports this expectation. Under the 'normal rainfall' scenario, agricultural GDP rises from US$2.1 billion in 2006 to US$3.6 billion by 2016 with 5.7 percent of annual growth rate (see Table 4.2). Because agricultural GDP growth is below total GDP growth (i.e., 5.8 percent) agriculture's share of GDP falls from 20.4 to 18.6 percent during 2006-16 under the normal rainfall scenario. However, this *gradual* decline in the importance of agriculture is still fairly optimistic given that this is the sector that is most vulnerable to climate variability. Results from the economywide model reveal the high sensitivity of agricultural GDP to varying rainfall patterns. On average, climate variability causes a total loss in agricultural GDP of US$2.2 billion over a ten-year period. This is equivalent to a reduction in agriculture's growth rate of one percentage point annually. With a lowered annual growth rate, the level of agricultural GDP by 2016 will be US$0.3 billion below what it have been under the normal rainfall scenario. Thus, climate variability greatly reduces Zambia's chances of achieving its national agricultural growth target of six percent per year, as set by the Comprehensive African Agricultural Development Program (CAADP).[16] As agriculture is more vulnerable to climate variability, losses in agricultural GDP account for more than half of overall economic losses despite the sector being only one fifth of the economy.

[16] CAADP is a compact amongst African countries to promote agricultural development and poverty reduction, to which Zambia will soon become a signatory (see Thurlow et al., 2008). CAADP is an initiative of the New Economic Partnership for African Development (NEPAD).

Figure 4.2: Loss in agricultural GDP due to climate **variability, 2006-2016**



Source: Results from the Zambian economywide model.
Note: Ten-year losses are cumulative for the whole 2006-2016 period, and not just the loss in the final year.

Agricultural losses are especially severe under the worst rainfall sequence, which replicates the rainfall patterns of the ten-year period between 1985/86 and 1994/95. If this rainfall sequence were to repeat itself over the next ten years, then accumulated agricultural GDP losses would amount to US$3.1 billion. This means that, during the worst sequence, agricultural GDP is 10.2 percent lower due to climate variability than what it would have been during a normal sequence. This is a substantial contraction of the agricultural sector and reflects the severity of the three droughts that took place during 1985-1995. Agriculture's average annual GDP growth rate during 2007-2016 would be 2.3 percentage points lower than under the normal rainfall scenario. Such a large decline in agricultural production would severely undermine the country's development efforts.

85 percent of national agricultural GDP losses caused by climate variability are in Zones I and IIa1

As the rainfall data showed in Section 2, there is considerable variation in rainfall across Zambia's five agroecological zones. By disaggregating the country into five different zones, the economywide model is able to capture spatial variation in the economic losses caused by climate variability. The zonal level contribution to the national agricultural economy varies significantly across the five zones. Table 4.2 reports zonal shares of agricultural GDP and national maize production, a sector most vulnerable to the climate shocks. The drought-prone Zones I and IIa are an important part Zambia's agricultural economy, generating more than half of national agricultural GDP, and almost two-thirds of national maize production.

Table 4.4: Agricultural GDP and national maize production by agroecological zone, 2006

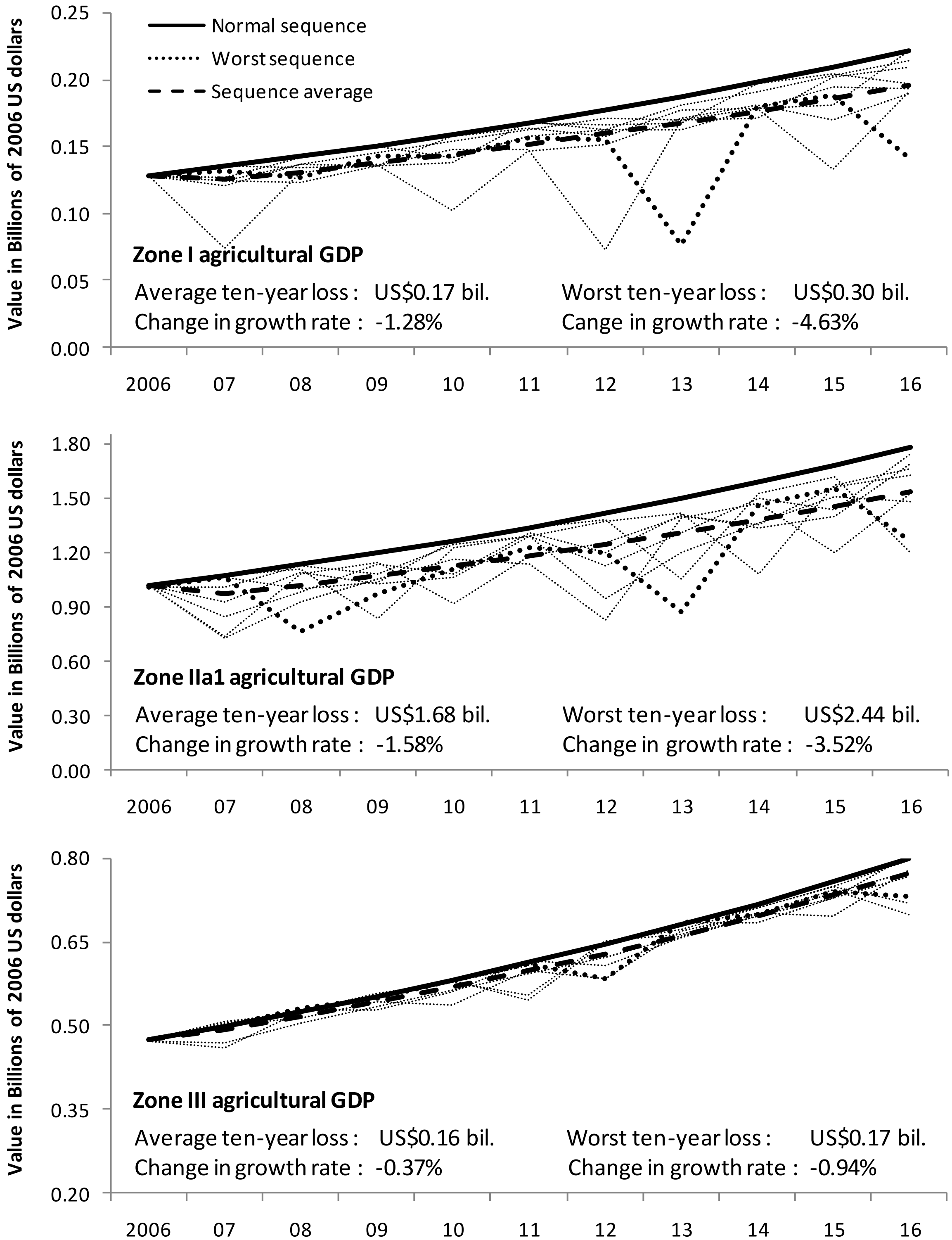
	Agricultural GDP		Maize production	
	Value (US$ mil.)	Share (%)	Level (1000 mt)	Share (%)
National	2,095	100.0	1,368	100.0
Zone I	128	6.1	169	12.3
Zone IIa1	1,016	48.5	692	50.6
Zone IIa2	174	8.3	179	13.1
Zone IIb	5	0.3	24	1.7
Zone III	474	22.6	304	22.2
Forestry	297	14.2	-	-

Source: 2006 Zambia social accounting matrix and CGE model.

Note: The Zambia model does not disaggregate the forestry sector across zones.

With a much larger share of national maize production and higher climate variability, agriculture in Zones 1 and IIa1 often suffers the most from bad rainfall patterns. This phenomenon is captured in Figure 4.3, which separately presents agricultural GDP growth path for three selected zones – two with highest climate variability (Zones I and IIa1) and one with the lowest climate variability (Zone III). Accumulated losses of zonal level agriculture are, on average, US$0.17 billion in Zone I, which had the smallest agricultural GDP of US$0.14 billion in 2006. Accumulated losses are US$1.68 billion in Zone IIa1, which has an initial agricultural GDP of more than US$1 billion. By contrast, even though agricultural GDP is about US$0.5 billion in Zone III, the accumulated losses due to climate variability in this zone is only US$0.16 billion, which is considerably smaller than that for Zone IIa1 (see Figure 4.3). This means that almost 85 percent of the agricultural GDP lost at the national level occurs in Zones I and IIa1. In contract, Zone III is relatively unaffected by climate variability. Higher climate variability also transfers into lower zonal economic growth rate. While growth in national agricultural GDP is, on average, one percentage point lower due to climate variability, larger declines in agricultural growth occur in Zones I and IIa1 (1.3 and 1.6 percentage points respectively), and more modest declines in Zone III (0.37 percentage points). Table 4.5 summarizes the spatial distribution of the costs of climate variability for all five agroecological zones. From this it is clear that the economic cost of climate variability falls heavily on Zambia's southern and central zones and declines rapidly from the south to the north of the country.

Figure 4.3: Loss in agricultural GDP in Zones I, IIa1 and III due to climate **variability, 2006-2016**



Source: Results from the Zambian economywide model.

Note: Ten-year losses are cumulative for the whole 2006-2016 period, and not just the loss in the final year.

Table 4.5: Impact of climate variability on agricultural GDP by agroecological zone, 2006-2016

	Average rainfall sequence			Worst rainfall sequence		
	Change in agric. GDP growth rate (%-point)	Ten-year cumulative losses (US$1000)	Share of cumulative economic losses (%)	Change in agric. GDP growth rate (%-point)	Ten-year cumulative losses (US$1000)	Share of cumulative economic losses (%)
National	-1.01	2,213	99.4	-2.29	3,132	98.9
Zone I	-1.28	172	7.8	-4.63	302	9.6
Zone IIa1	-1.58	1,682	76.0	-3.52	2,442	78.0
Zone IIa2	-0.93	182	8.2	-1.64	175	5.6
Zone IIb	-0.86	5	0.2	-2.44	9	0.3
Zone III	-0.37	158	7.1	-0.94	169	5.4

Source: Results from the Zambian economywide model.
Note: Agricultural GDP at the zonal level excludes forestry, which is not disaggregated in the model. Total zonal impacts are below national impacts. Ten-year losses are cumulative for the whole 2006-2016 period, and not just the loss in the final year.

If Zambia's rainfall patterns of 2006-2016 were to replicate those of the 1985/86 to 1994/95 period in the worst rainfall sequence, then the economic losses caused by climate variability would be even more heavily concentrated in Zones I and IIa1. As shown in Table 4.5, almost 90 percent of the losses in agricultural GDP would take place in these two southern and central zones. Moreover, the worst rainfall sequence is especially severe for the southern Zone I, where the droughts of the early to mid-1990s were pronounced. By contrast, Zones IIa2 and III are affected less than other zones during this worst rainfall sequence since neither zone experienced severe drought conditions during these years (see Table 2.1). This highlights the spatial complexities of Zambia's rainfall patterns and the importance of considering spatial variation when assessing the consequences of climate variability. For instance, while national agricultural GDP losses increased by 40 percent under the worst rainfall sequence, they increased by 75 percent in drought-prone Zone I.

Climate variability reduces maize production by at least 30kg per capita and jeopardizes food security

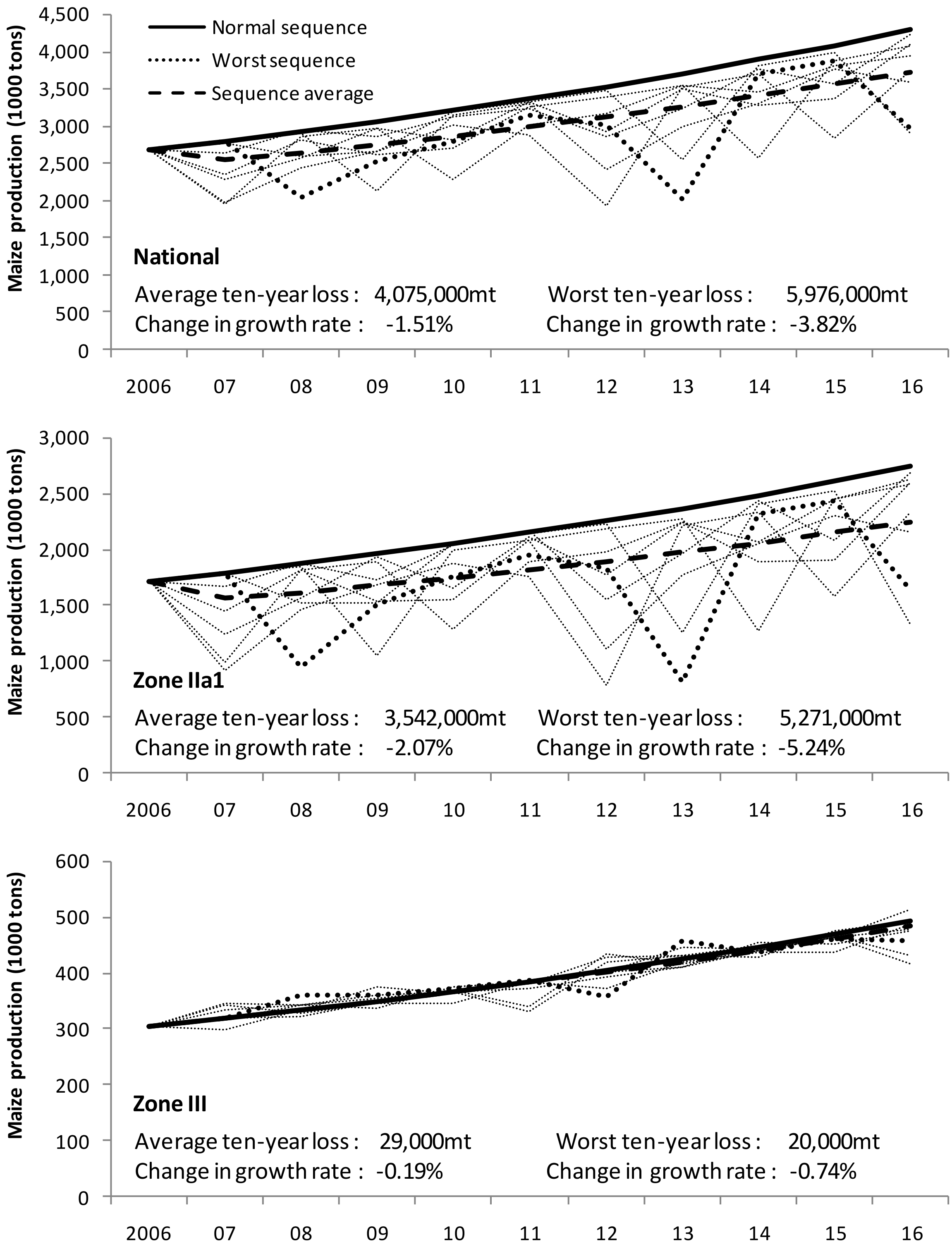
The economywide model includes detailed crop and livestock production across the five agroecological zones. This allows us to estimate impacts on food crop production, and by implication, on food security. Here we focus on maize production since this is one of the most important food crops in Zambia and is grown and consumed throughout the country. While cassava is also an important food crop, it grows mainly in Northern Zambia and is less vulnerable to climate variability than maize. In Section3 we have presented the hydro-crop model results of climate variability on maize yields using the historical data of the last 32 years. In this section, we estimate the impact of climate variability on maize production as well as it economywide effect on aggregate economic indicators (GDP and agricultural GDP). Figure 4.4 shows such effects on maize production at national level as well as for the two largest maize production zones in the country (i.e., Zones I and III). The figure shows that without climate variability, maize production grows at 4.8 percent per year from 2.7 million tons in 2006 to 4.3 million tons by 2016. This is a result of expansion in maize cultivated area and improvements in maize yields.[17] The negative effect of climate variability on maize production is primarily through lowering yields, together with modest declines in the cultivated land area during major drought and flood seasons (see Table 4.1 for the main channels through which climate variability affect crop production). Accordingly, as shown in Figure 4.4 national maize production is below that of the normal rainfall scenario once climate variability is account for.

The cumulative losses in maize production over the entire 2006-2016 period are four million tons on average. This is equivalent to a drop in maize's production growth by 1.5 percentage points in each year. Almost all of the losses are concentrated in Zone IIa1, where climate variability is high and where most of the country's maize producers are situated, including larger-scale farmers. By contrast, Zone III, which is also a major maize producing region, is far less affected by climate variability. Moreover, when there are severe southern droughts but relatively normal conditions elsewhere, the less drought-stricken regions benefit slightly as farmers in these areas respond to the higher maize prices caused by droughts in the other parts of the country and expand their maize production. Such expansion in maize production is the result of more intensive farming by employing more inputs, since land allocations are determined at the start of a given season. By devoting more labor and other inputs towards maize production, farmers in the less drought-stricken regions improve land productivity and reduce the gap between area planted and area harvested. However, while the economywide model captures these 'adaptive' responses or regional linkages, their effect is relatively small due to land constraints and farmers inability to predict extreme drought and flood events elsewhere in the country. As such, the increase in Zone II maize production during southern drought years is relatively small.

One measure of food security is per capita food availability supplied by domestic production. Table 4.6 shows per capita maize production for the five agroecological zones and for the country as a whole. Per capita maize production in 2006 is an average 125 kilograms (kg) per person at the national level. Although maize is grown throughout Zambia, its share of household consumption baskets varies due to different patterns of crop mix across the agroecological zones. Per capita maize production is lowest in the western Zone IIb, where households consume larger shares of sorghum and millet. Similarly, per capita maize production in Zone III is lower than the national average, since cassava is grown more widely in this zone. However, despite these spatial differences in maize dependency, this crop is a reasonable measure of food security at the national and zonal level as its availability is generally close or more than 100 kg per person across the zones in a normal rainfall year.

[17] In the normal rainfall scenario cultivated area under maize production increases from 1.4 million hectares in 2006 to 1.8 million hectares in 2016. During the same period, national average maize yields rise from 2.2 to 2.6 tons per hectare. Note that yields are calculated using harvested rather than planted land area.

Figure 4.4: Loss in national and zonal maize production due to climate **variability, 2006-2016**



Source: Results from the Zambian economywide model.

Note: Ten-year losses are cumulative for the whole 2006-2016 period, and not just the loss in the final year.

Table 4.6: Per capita maize production by agroecological zone, 2006-2016

		Average per capita maize production (50kg bags per person)					
		I	IIa1	IIa2	IIb	III	All
2006	Initial	2.77	3.03	2.69	0.86	1.84	2.49
2016	Normal sequence	3.65	3.98	3.57	1.12	2.43	3.29
	Average sequence	3.26	3.26	3.37	0.99	2.39	2.90
	Worst sequence	2.15	2.39	3.24	0.64	2.27	2.34

Source: Results from the Zambian economywide model.

The model results indicate that, under the normal rainfall scenario maize production grows faster than the population and per capita availability of maize rises from 125 kg in 2006 to 165 kg by 2016, a level that can be met with domestic food and feed demand for maize even with 6.7 percent of annual GDP growth. However, as discussed above, climate variability lowers maize production, causing per capita availability to rise to 145 kg per person by 2016, only 20 kg more than the current (2006) level. Moreover, if the rainfall patterns in the next 10 years are similar as those described under the worst rainfall sequence, per capita maize availability supplied by domestic production by 2016 declines to a level below that in 2006. The detrimental effects of climate variability on food insecurity are especially pronounced in drought-prone Zones I and IIa1. Climate variability therefore greatly reduces food availability in Zambia, thus necessitating food imports and aid during periods of severe droughts.

Climate variability will keep 300,000 more people in poverty over the next decade

Apart from its adverse effects on basic food security, climate variability has large impacts on household incomes and poverty. This can be seen in Figure 4.5, which shows the national poverty headcount rate over the next years resulting from model simulations. The poverty rate is the share of the population whose per capita expenditure falls beneath the national poverty line.[18] According to this welfare measure, poverty under the normal rainfall scenario falls from 67.9 percent in 2006 to 52.2 percent in 2016.[19] This is still insufficient to meet the first Millennium Development Goal of halving 1991 poverty by 2015 (i.e., achieving a poverty headcount of 36.1 percent), because the relatively modest poverty reduction in the past. However, poverty reduction under the normal rainfall scenario would be sufficient to offset population growth of two percent per year such that the *absolute* number of poor people falls from 7.44 million in 2006 to 6.96 million in 2016. This would be first time in the country the absolute number of poor has declined since poverty was first measured in Zambia in 1991.

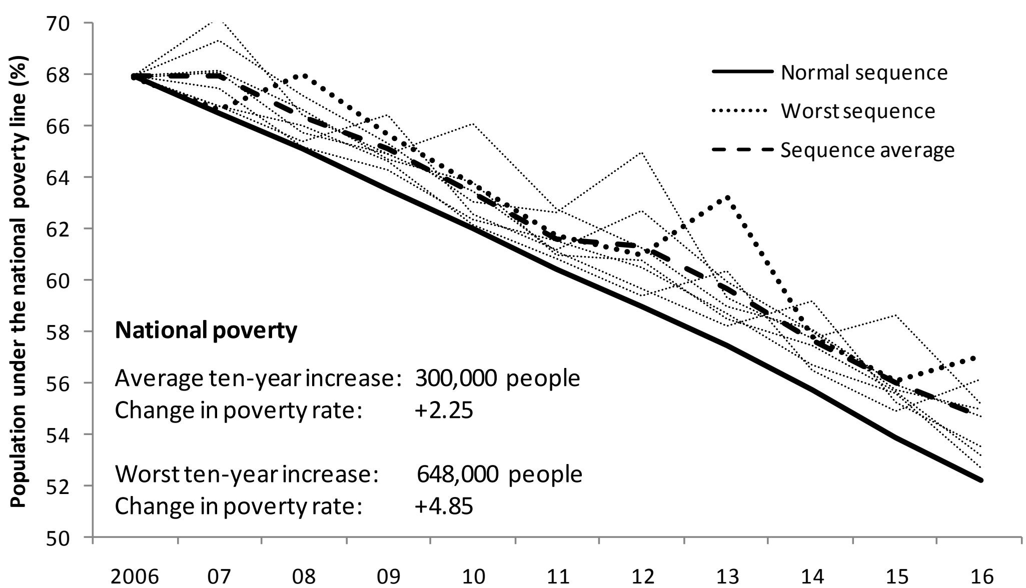
However, climate variability will slow down poverty reduction over the next ten years. As shown in Figure 4.5, the national poverty rate averaged from the 30 rainfall sequence scenarios (the line called sequence average) is above the line representing the national poverty rate under the normal rainfall scenario. On average, climate variability increases the national poverty by 2.3 percentage points by the

[18] The national poverty line in 2004/05 was US$300 per person per year or US$0.8 per day. Converted to 2006 current prices, the poverty line is US$496 per person per year or US$1.36 per day.

[19] The 2005/05 Living Conditions Monitoring Survey (LCMS) is used to estimate poverty changes due to the unavailability of the 2006/07 survey. The economywide model is benchmarked to 2006, and we have to effectively assume that poverty has not change greatly between 2004/05 and 2006.

end of the ten-year period. There are thus 300,000 more people living under the poverty line in 2016 than there would have been without climate variability. Under the worst rainfall sequence, the national poverty rate is higher by 4.9 percentage points by 2016 and there are 650,000 more people living under the poverty line in 2016 compared to the normal rainfall scenario. This is enough to offset any reduction in the number of poor people in Zambia and the absolute number of the poor will not decline by 2016. Thus, if Zambia were to experience a ten-year rainfall pattern similar to that of 1984/85 to 1994/95, then most of the country's potential reductions in poverty over the next ten years would be lost, and the number of poor people in Zambia would rise from its current 7.4 million to 7.6 million by 2016.

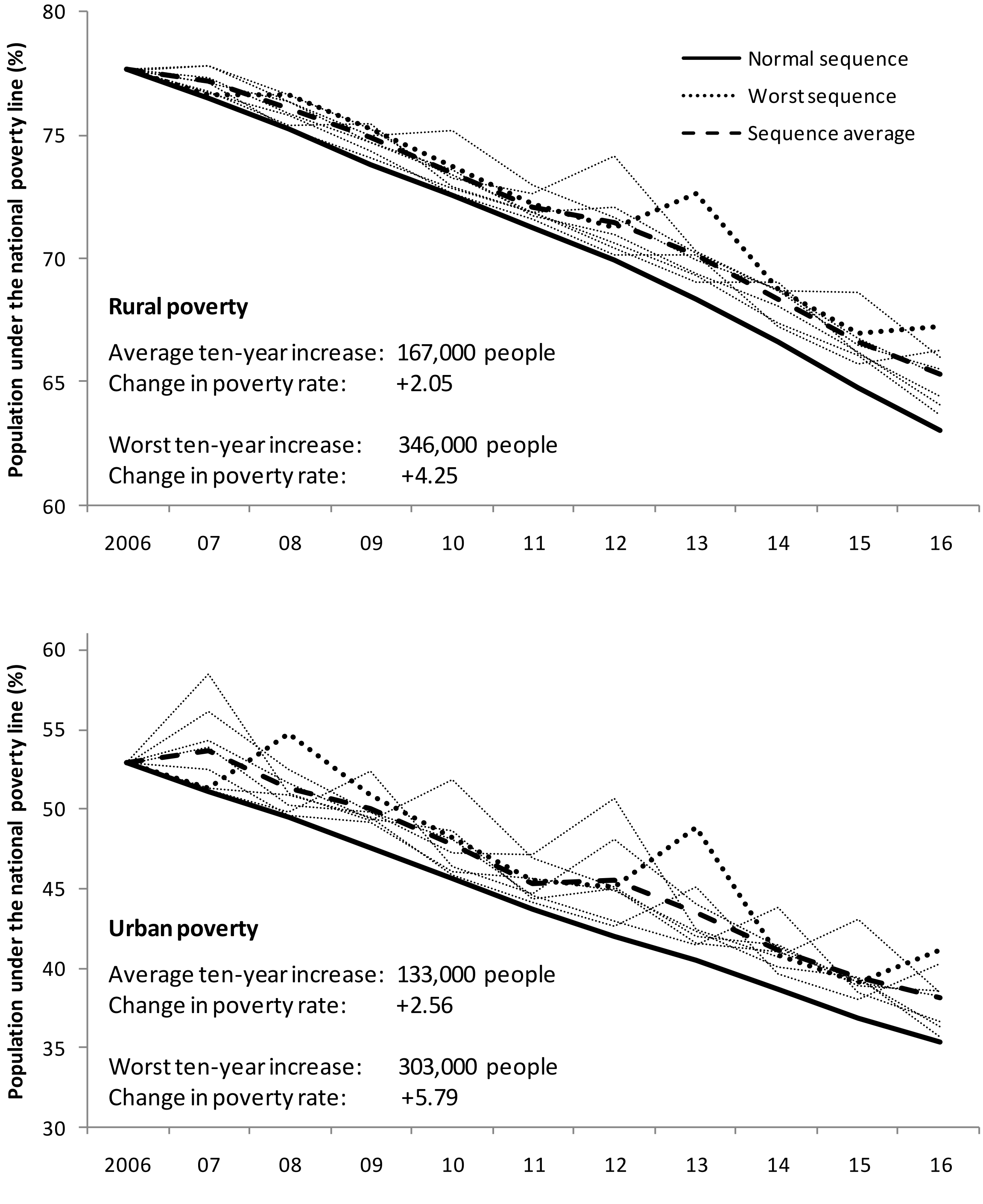
Figure 4.5: Increase in the national poverty headcount rate due climate **variability, 2006-2016**



Source: Results from the Zambian economywide model

Finally, Figure 4.4 shows the impact of climate variability on rural and urban poverty. The results indicate that while agriculture is the primary impact channel through which climate variability affects the Zambian economy, it has implications for poverty reduction in *both* rural and urban areas. This is true for two reasons. First, one third of Zambia's urban population is engaged in agricultural production (Thurlow et al., 2008). Thus, while agricultural incomes are not especially important in urban areas, changes in rainfall patterns still affect urban incomes. Secondly, and more importantly, food consumption is a large share of urban households' expenditure baskets. Thus, real urban incomes are influenced by changes in agricultural production and prices. As a result of these two characteristics, the declines in agricultural production caused by climate variability and the resulting increases in food prices reduce urban real incomes. Accordingly, two fifths of the increase in poverty caused by climate variability takes place in urban areas (e.g., 133,000 people out of 300,000 at the national level). This result further indicates the importance of measuring the economywide effects of climate variability (i.e., beyond direct impacts on agricultural production and farmers). This is particularly true when estimating its welfare implications. In the case of Zambia, these welfare implications are pronounced.

Figure 4.6: Increase in rural and urban poverty headcount rates due to climate variability, 2006-2016



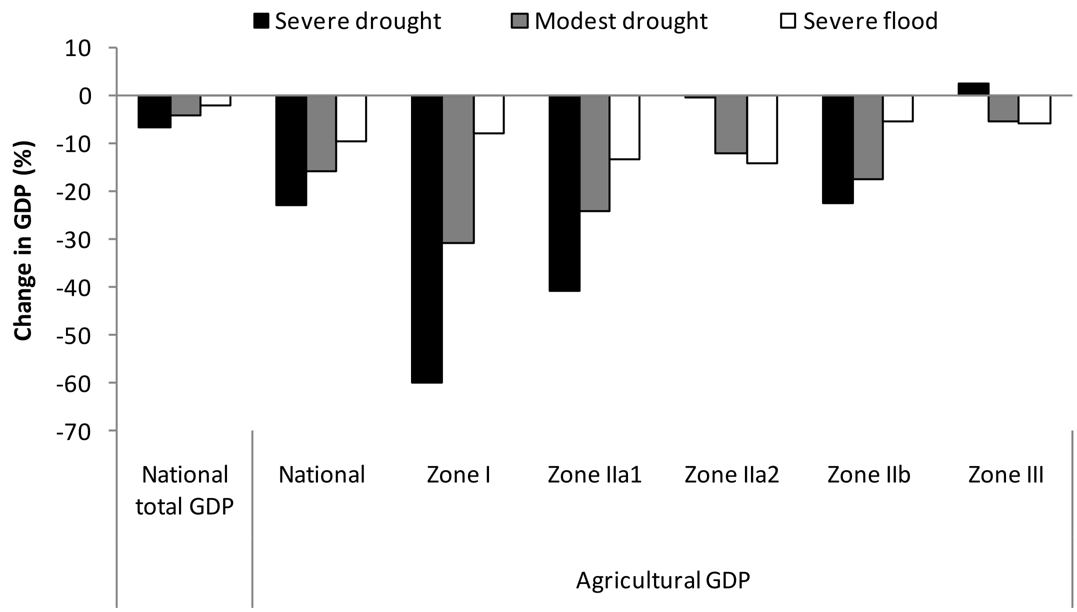
Source: Results from the Zambian economywide model

Severe droughts and floods dramatically lower growth and increase poverty in the drought/flood years

The above analysis focuses on the economic impact of climate variability over a period of ten years and did not discuss effects in any particular year. The above analysis is important to understand the general impact of climate variability over relatively longer periods. However, by focusing on alternative climate sequences, it does not reflect the severity of economic impacts during particularly severe drought or flood years. Thus, in this subsection we present some results from a single-year in which a drought or flood occurs. We call such effects the 'immediate impact' of drought/flood. More specifically, we present the economic costs for a year in which a severe drought occurs (e.g., 1991/92), a year in which a modest drought occurs (e.g., 1994/95) and a year in which a severe flood occurs (e.g., 2006/07). In order to make the results from the three events comparable, it is necessary to adopt the same starting point for each of the three simulations (i.e., the same level and structure of economic activity). Accordingly, in each of the three climate shock scenarios we impose the shock at the same point in time – in this case the second year in the model simulation (i.e., 2007). Thus, for example, we are not estimating the impact of the actual 1991/92 drought, but rather asking what the impact would be of a similar magnitude drought were it to have taken place in 2007. Since we ask the same question for the 1994/95 drought and the 2006/07 flood, it is possible to directly compare the results from the three climate shock scenarios.

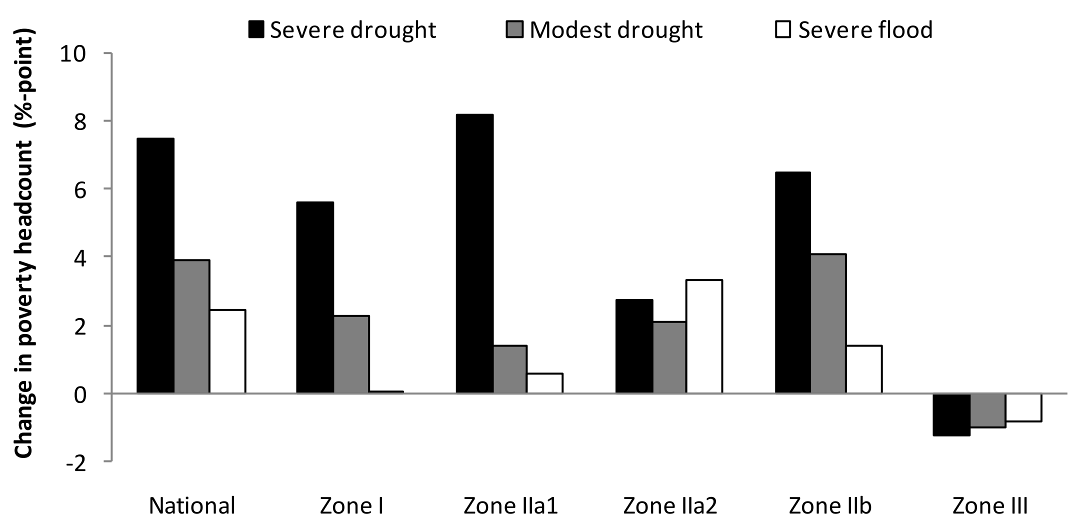
Figure 4.7 shows the impact of such climate shocks in an individual year on total and agricultural GDP. A severe drought of the same magnitude as one experienced in 1991/92 would cause national agricultural GDP to decline by 22.7 percent compared with a normal rainfall situation in the same year. This national-level outcome is driven by large declines in agricultural production in the three zones worst affected by the drought (i.e., Zones I, IIa1 and IIb). Overall, the collapse in agricultural production and the negative impacts taking place in other sectors of the economy causes total GDP to fall by 6.6 percent in this year. A modest drought like the one of 1994/95 can also produce large negative outcomes for the country if it occurs again in the future. With such drought shock, total GDP falls by 4.0 percent and the adverse effects of the drought are again concentrated in Zambia's three drought-prone zones, albeit with some declines in Zone III agricultural GDP due to the wider coverage of the 1994/95 drought (see Table 3.1). By contrast, a severe flood, similar to the one experienced during 2006/07, affects zones more evenly but has a less pronounced impact on the overall economy. Thus, while Zone III's agricultural GDP declines the most under the severe flood, the impact on other zones is far smaller than under even the modest drought. As a result, total GDP only declines by 2.3 percent under the severe flood scenario, which is well below the declines in GDP under either of the two drought scenarios.

Figure 4.7: Change in GDP during severe drought and flood years



Source: Results from the Zambian economywide model.
Note: Severe drought reflects the climate conditions in 1991/92; modest drought is 1994/95; and severe flood is 2006/07. Zonal agricultural GDP excludes forestry, but this is included in national agricultural and total GDP.

Figure 4.8: Change in poverty headcount rate during severe drought and flood years



Source: Results from the Zambian economywide model.
Note: Severe drought reflects the climate conditions in 1991/92; modest drought is 1994/95; and severe flood is 2006/07. The zonal poverty rates are for farm households only (i.e., 80 percent of the total population), whereas the national poverty rate includes all households.

Severe droughts and floods also have large impacts on household incomes in those particular years. Figure 4.8 shows changes in the poverty headcount in the particular year under each of the three climate shock scenarios. The national poverty rate rises dramatically by 7.5 percentage points in a year under the severe drought scenario. Were this severe drought to take place in 2007, then this would imply an increase in the number of poor people by 836,000 from the level in the same year without drought.[20] Poverty also rises significantly in the year with the modest drought, as the poverty rate increases by 3.9 percentage points and the absolute number of poor people rising by 435,000 in a year. Finally, the national poverty rate rises by 2.4 percentage points in the year with severe flood, which pushes 273,000 more people below the poverty line in that year.

Table 4.4 summarizes the findings from the above analysis of the impacts of climate variability on economic growth and poverty. The results have clearly indicated that climate variability has large adverse consequences for both economic growth and poverty reduction. In the next section we examine alternative investments to reduce these consequences.

Table 4.4: Summary of key results from the impact assessment of climate variability

	Ten-year climate sequences		One-year drought and flood events		
	Average over 30 sequences	Worst sequence	With severe drought	With modest drought	With severe flood
Change in GDP growth rates (%-point)					
Total GDP	-0.43	-0.90	-6.6	-4.0	-2.3
Agricultural GDP	-1.01	-2.29	-22.7	-15.7	-9.4
Cumulative or total loss in GDP, 2006-16 (US$ billion)					
Total GDP	4.3	7.1	2.6	1.6	0.9
Agricultural GDP	2.2	3.1	1.8	1.2	0.7
Change in national poverty (%-point)					
	2.2	4.9	7.5	3.9	2.4
Increase in absolute poor (1000s)					
	300	648	836	435	273

Source: Results from the Zambian economywide model.
Note: Ten-year losses are cumulative for the whole 2006-2016 period measured in 2006 prices; one-year total losses are for the year in which the extreme climate event takes place (also measured in 2006 prices); 'severe drought' replicates the 1991/92 drought; 'modest drought' replicates the 1994/95 drought; and 'severe flood' replicates the 2006/07 flood.

[20] The percentage point increase in the poverty rate would remain largely unchanged irrespective of the year in which the drought takes place. However, the absolute increase in poor people obviously depends on the size of the population, which is increasing over time. We are modeling the impact of droughts and floods in the second year of the model simulation (i.e., 2007), when the total population of Zambia was 11.2 million.

5. Additional impacts on growth and poverty from climate change

5.1 Climate change and agricultural crop yields – HC model results

Even with sufficient mitigation measures the current scientific consensus holds that greenhouse gas emissions and atmospheric concentrations are set to increase for some decades to come. Consequently, global mean surface temperatures will continue to rise long after peak emissions are passed. This global warming is expected to affect global water and food systems in profound ways, as identified by the International Panel on Climate Change (IPCC, 2007). The most serious of these impacts are mediated via water due to hydrological changes (Rogers, 2008). However, besides water, there are two other opposing factors that may also determine climate change's impact on agriculture. On the one hand, rising atmospheric CO_2 concentrations should increase yields through a process known as 'carbon fertilization'. Conversely, rising temperatures may substantially reduce yields for some crops. However, amongst these three factors, it is changes in the availability of water caused by climate change that has by far the largest consequences for agriculture (Houghton, 2004; Hulme, 1996).

Given Zambia's latitude, rising temperatures caused by climate change are likely to reduce crop yields in the country. Conversely, studies have shown that the effects of carbon fertilization should raise crop yields.[21] Given these opposing impacts and the uncertainties surrounding them, especially at the country and crop-level, the effects of temperature changes and carbon fertilization on crop yields are not examined in this study. Instead, we focus on the yield impacts caused by hydrological changes.

A number of global climate change scenarios have been simulated. For our study we use the SRES B1a scenario of the HadCM3 model, which is a coupled atmosphere-ocean general circulation model developed at the Hadley Centre (henceforth refer to as HadCM3/B1a).[22] From this scenario, we obtained mean changes in precipitation, minimum and maximum daily average temperature, relative humidity, and wind speed for grid cells in Zambia for the next 20 years until 2025. The HadCM3/B1a scenario was selected because it represents a future climate where rainfall declines and temperatures increase throughout the Zambia, thus potentially jeopardizing agricultural production. We chose the year 2025 because it is the year closest to the 2006-2015 period analyzed in the previous section.[23] Accordingly, the changes in our analysis will be less pronounced than in other studies, since 2025 is considerably closer than the distant projections used elsewhere (e.g., 2050 or 2100). Moreover, the IPCC report indicates that alternative global scenarios show little variation until 2030, thus making the use of multiple scenarios less attractive for the purposes of our analysis.

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[21] Recent studies find that carbon fertilization effects may be overestimated in earlier studies (Long et al., 2006)

[22] The data for Zambia was obtained from the IPCC Data Distribution Center (http://www.ipcc-data.org/). The B1 storyline and scenario family describes a convergent world with the global population that peaks in midcentury and declines thereafter and with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate initiatives.

[23] Economic models become substantially more inaccurate beyond 10-15 years, which recommends 2025 as the maximum range for our analysis.

Mean monthly changes in climate variables from the HadCM3/B1a scenario were downscaled to Zambia's 30 meteorological stations (see Figure 2.1). These were then applied to the historical monthly weather observations for 1976-2007 in order to construct new climate data reflecting climate changes in 2025 as per the SRES B1a scenario. The new climate data were then analyzed using the crop-water module described in Section 2 in order to derive yield effects from climate change.

Considerably uncertainty surrounds the effects of climate change, especially at the country level. Accordingly, two additional climate change scenarios besides the HadCM3/B1a scenario were created to examine crop yield responses under larger changes in rainfall and temperature. In the first scenario, we assume that temperatures increase by 2°C in every month throughout the country and rainfall declines by 15 percent from the observed 1975-2007 series (i.e., the T2P-15 scenario). In the second scenario, we also assume temperatures increase by 2°C but rainfall now increases by 15 percent from the 1975-2007 series (i.e., the T2P+15 scenario). All three climate change scenarios represent mean changes in future climate at a fixed year level from the historical climate. It therefore does not account for a gradual evolution of climate change. The reason for this simplification is that we use the index sequential method (Prairie et al. 2006) to resample climate series in order to create sequences to be used in the economic model. This implicitly assumes a stationary climate series and so does not allow for gradual changes.

Unlike the HadCM3 scenario, the two additional scenarios are not based on global climate model projections but are used to represent more dramatic changes for Zambia in the intermediate term. They assume uniform changes of temperature and precipitation imposed on the historic temperature and precipitation sequence of all the 30 weather stations of Zambia for the period 1972-2007. These kinds of hypothetical scenarios are often used in climate change impact assessment and adaptation studies, to examine the responses of a study region to a wide range of changes (Zhu et al. 2005; Yates et al. 2007). The assumed 2°C increase in temperature and 15 percent decline of rainfall of the T2P-15 scenario may not necessarily happen by 2025 but the chance that it happens later cannot be underestimated, given the fact that many climate models projected a drying trend for Southern Africa and the current level of global green house emission already exceeds the maximum level projected in the IPCC emission scenarios (IPCC 2007). Likewise, the chance that the warmer and wetter T2P15 scenario happens in the future cannot be excluded, as there are certain global climate models that project a wetting trend for this region (IPCC 2007). It is the uncertainties associated with emission scenarios and climate model projections that make the hypothetical scenarios a useful means to look into a broader possibilities of climate change outcome.

The climate change scenarios do not explicitly introduce changes in variability into observed meteorological data, but rather cause changes in mean climate. We then analyze the impact of these mean climate changes on crop yields using the hydro-crop model. Table 5.1 gives the mean and average standard deviation of changes in maize yields relative to the estimated yields for 1976-2007 under each of the three climate change scenarios. Under HadCM3/B2 scenario, yields decline relative to the estimated historical trend of 1976-2007 for all agroecological zones except for Zone IIb, in which maize yields increase slightly relative to historical trends. Given that rainfall is generally declining under

HadCM3/B2 scenario, this slight increase in Zone IIb's yield is a result of complex interactions of multiple climate variables that jointly determine crop water requirements and soil moisture dynamics. Overall, we conclude that, compared with the past period of 1976-2007, climate change with less rainfall and higher temperature (i.e., the HadCM3/B2 scenario) leads to a one percent reduction in maize yields for Zones I, IIa1 and IIa2 by 2025 and no changes in Zones IIb and III. As the scenario does not capture the changes in the patterns of rainfall variation, the standard deviations of maize yields from the historical trends of maize yields have a similar magnitude to the changes in mean. Although HadCM3/B2 scenario results in only small changes in maize mean yield relative to its historical trends, impacts in a particular year can be much larger. For example, in a severe drought year similar as that of 1991/92 maize yield is 4 percent lower than it was in 1991/92 when there is climate change effect in the future.

Table 5.1: Changes in maize yields relative to historical yield trends under climate change scenarios

	HadCM3/B1a scenario		T2P-15 scenario		T2P+15 scenario	
	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
Zone I	-0.009	0.013	-0.058	0.069	0.032	0.044
Zone IIa1	-0.010	0.014	-0.057	0.058	0.042	0.056
Zone IIa2	-0.013	0.013	-0.038	0.041	0.018	0.022
Zone IIb	0.001	0.005	-0.045	0.042	0.032	0.045
Zone III	-0.002	0.005	-0.014	0.022	0.005	0.015

Source: Results from the hydro-crop model.
Note: HadCM3/B1a is the SRES B1a scenario from the HadCM3 global circulation model (Hadley Center); T2P-15 and T2P+15 scenarios assume that temperatures in Zambia rise by 2 percent throughout the country, while rainfall either rises or falls by 15 percent.

Under T2P-15 scenario, 4-6 percent declines in maize yields relative to the historical trends are observed in all agroecological zones except for Zone III, where the reduction is only 1.4 percent. 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 percent drop in maize yields throughout most of Zambia if rainfall declines by 15 percent and temperature rises by two degrees in the future. Under T2P+15 scenario, the maize mean yield relative to the historical trends increases by 3-4 percent for Zones I, IIa1 and IIb. There is a 2 percent increase for Zone IIa2 and a slight increase for Zone III. In both T2P-15 and T2P+15 scenarios, the wetter Zone III is fairly resilient to climate changes in terms of crop yield responses to declines or increases in rainfall. By contrast, the four other drier zones are likely to face larger changes in crop yields if future rainfall declines or increases and temperatures rise.

5.2 Climate change and economic growth – DCGE model results

In Section 4 we used the DCGE model to estimate the economic impact of climate variability by simulating each of 30 possible climate patterns for a 10 years' period drawn sequentially from historical data for the period 1977-2007. In this section we use similar method to estimate the extent to which climate change affects the broad economy through its impact on crop yields (see Table 5.1). Thus, corresponding to each of the three climate change scenarios discussed above, we first adjust historical rainfall data to reflect the new weather conditions predicted in the climate model. These three *synthetic* datasets now contain the effects of *both* historical climate variability and future climate change. We then redraw the 30 rainfall patterns sequentially from each of synthetic datasets and compare the average outcomes under these new climate change scenarios with the average outcomes already discussed in the previous section under the climate variability scenarios. The differences between these average outcomes can thus be solely attributed to climate change causing crop yields to change. The question that these modeling exercises try to assess is: what would be the impact of climate variability over the next ten years if the possible effect of climate change on crop yields occurred during the 2007-2016 period? The main economywide results from the climate change scenarios are shown in Table 5.2.

Table 5.2: Impact of climate change on economic growth and poverty (deviations from the results of the normal rainfall scenario)

	Change in annual growth rate (%-point)		Ten-year cumulative losses in GDP (US$ billion)		Change in national poverty rate (%-point)	Increase in absolute number of the poor (1000s)
	Total GDP	Agric. GDP	Total GDP	Agric. GDP		
Mean of 30 sequence scenarios, 2007-2016						
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 sequence scenarios, 2007-2016						
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

Source: Results from the Zambian economywide model.

The top half of Table 5.2 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 its historical patterns without taking account of possible climate change, the average decline in the annual growth rate of total GDP is 0.4 percentage points. The first row of Table 5.3 re-reports the results from Figure 4.1 in Section 4. Incorporating the effects of climate change produces mixed results. The loss in total GDP growth is slightly larger under the HadCM3/B1a scenario, but is substantially larger under the T2P-15 scenario, which captures potential declines in average rainfall due to climate change. Moreover, the higher average rainfall under the T2P+15 scenario dampens the adverse effects of climate variability on growth, and the average decline in GDP growth is smaller than in the case without climate change (Table 5.2). These results indicate that if climate changes cause less rainfall every year, economic annual growth rate would decline further by between 0.05 percentage points (under HadCM3/B1a scenario) and 0.20 percentage points (under T2P-15 scenario) in each of the next 10 years. However, if climate changes cause more rainfall under T2p+15 scenario, the the GDP growth rate would be slightly higher than without climate change (0.14 percentage points). The implications of these seemingly small changes in the total GDP growth rate become more substantial once their effects are accumulated over the ten-year simulation period (i.e., 2007-2016). For instance, cumulative declines in total GDP under T2P-15 scenario are US$6 billion (in 2006 prices and 1.7 billion more than that without climate change effects) compared to US$3 billion under T2P+15 scenario (1.3 billion less than that without climate change effects). Even under the modest HadCM3/B1a scenario, climate change increases the costs already accrued due to climate variability by an additional US$0.37 billion over the ten-year period (4.69 billion in total in 2006 prices – see Table 5.2). Thus while the economic implications of climate change may appear inconsequential at any given point in time, its gradual impact on both total and agricultural GDP becomes more significant over time.

The second part of Table 5.2 presents deviations in outcomes from the worst rainfall scenario reported in Section 4. If Zambia's rainfall patterns over the next 10 years replicate those observed during the 1984/85 to 1994/95 period, then the total growth rate will be 0.9 percentage points lower than it would have been under a normal rainfall scenario without variability (see Section 4.2). However, incorporating the impact of climate change derived from HadCM3/B1a scenario, the drop in GDP growth rates rises to 1.01 percentage point (i.e., a further 0.1 percentage point decline). Over ten years, this lowered GDP growth rate results in an accumulated loss in GDP by US$0.7 billion (in 2006 prices). With the more pessimistic T2P-15 scenario,additional cumulative losses would rise dramatically to US$9.9 billion, which is almost US$3 billion more than without taking into account climate change effects. Conversely, if the more optimistic T2P+15 scenario is accurate, then a small GDP loss would happen and the accumulated losses would fall to US$5.08 billion, which is US$2 billion less than in the situation without climate change effect and with climate variability only.

Finally, in last two columns of Table 5.2 the impact of climate change on national poverty rates and the absolute number of poor people by 2016 are reported. Since climate change further increases climate variability's effects on agricultural production and food prices, there is significant difference in poverty outcomes between the three climate change scenarios. For instance, even with the modest HadCM3/B1a scenario the national poverty rate in 2016 will be 0.24 percentage points higher than it would if there was no climate change (i.e., rising poverty rate by 2.5 percent instead of 2.3 percent by 2016). Thus, climate change increases the absolute number of poor people in 2016 by 32,000. Similarly, under the worst rainfall sequence together with the HadCM3/B1a scenario, the poverty rate would be 0.6 percentage points higher as a result of climate change. These deviations in poverty rates are substantially larger for the two hypothetical climate scenarios (i.e., less rainfall increases poverty while more rainfall lowers poverty).

Overall, in Zambia, the additional impact of future climate change on economic growth and poverty is substantially smaller than that of climate variability (based on historical patterns). Even under more pessimistic climate change scenarios, effects are less than half those from the climate variability scenarios. However, it should be noted that the climate change scenarios in this study did not capture the possible change in climate variability and hence can only partially provide illustrative results for potential climate change impacts in Zambia. We find that the expected changes remain fairly small under HadCM3/B1a scenario. However, the impacts can be more pronounced if larger changes in rainfall and temperature occur, as illustrated by the two hypothetical climate change scenarios, or climate variability patterns change. Moreover, while the average change over the longer-term is relatively small, there can be considerable impacts in specific years, especially if there is even less rainfall than during the severe drought years observed in Zambia's history. Moreover, because we did not explicitly capture any possible changes in the patterns of climate variability caused by climate change, worsening climate variability exacerbated by climate change may have unexpected subnational impacts on the Zambian economy. This possibility emphasizes the importance investing in climate mitigation and reducing Zambia's vulnerability to extreme rainfall events.

6. Summary and conclusions

Zambia's economic performance over the last three decades has been hampered by high levels of climate variability and frequent and severe droughts and floods. Even in more recent years, when the country's economy has performed better, there is still considerable variation in the growth rate of the agricultural sector. In order to assess the consequences or impacts of climate variability on economic growth and poverty reduction in Zambia, we developed an integrated analytical framework. First, we used historical climate data and a hydro-crop model to estimate the impact of climate variability on crop yields over the last three decades. This analysis was done at the crop level for each of Zambia's five agroecological zones, supported by the identification of zonal level extreme weather events using a drought index analysis. Drawing on these results, we then developed an economywide CGE model and analyzed changes in crop yields due to climate variability on economic growth and poverty. In doing this, we considered not only the main impact channel of yield declines, but also other indirect impact channels, including effects on crop areas, livestock stocks, and depreciation of physical capital.

Findings from the economywide modeling assessment suggest that climate variability has a pronounced negative effect on economic growth. We estimate that, on average, climate variability reduces Zambia's GDP growth rate by 0.4 percentage points per year, which costs the country US$4.3 billion over a ten-year period. These losses reach as high as US$7.1 billion under Zambia's worst rainfall sequence. Agriculture is the primary impact channel and is especially vulnerable, with climate variability reducing agriculture's annual GDP growth rate by one percentage point and over two percentage points during the worst rainfall sequence. This will greatly reduce Zambia's chances of achieving it national development goal of strengthening agricultural and rural income growth. Indeed, we find that negative effect of climate variability is especially severe for maize, the country's main food staple crop, and that it therefore greatly threatens basic food security in both rural and urban areas. Most of negative impacts of climate variability occur in the southern and central regions of the country, and it is there that food insecurity is most vulnerable to climate shocks. Overall, climate variability keeps 300,000 people below the national poverty line by 2016. While most of these people live in rural areas, climate variability also greatly increases urban poverty due to higher food prices and lower real urban incomes. Number of the poor rises substantially during the period in which if rainfall patterns are similar to those experienced in 1985-1995, when the country experienced a series of severe droughts. Indeed, national poverty rate may rise by as much as eight percentage points in particularly severe drought years. Climate variability has thus played a significant role in undermining economic development in Zambia in the past and will continue to do so in the future.

We also examined whether climate change will exacerbate or dampen the negative consequences of climate variability. Here considerable uncertainty exists, especially regarding change in future rainfall patterns. Accordingly, while we used a well known climate change projection model, we also conducted two hypothetical scenarios' analysis. We find that current patterns of climate variability dominate potential climate change in the near future until 2025. However, differences in assumptions regarding rainfall changes greatly influence both the size, and to a lesser extent, the direction of the economic impact of climate change. If rainfall declines by 15 percent, then climate change would enhance the negative effects of climate variability by a factor of 1.5. It is also enough to leave an additional 30,000 people below the poverty line over a ten-year period. Moreover, the effects of climate change and variability compound each other, with the number of poor people remaining below the poverty line rising to 74,000 if climate change is coupled with Zambia's worst ten-year historical rainfall pattern. Thus, climate change may further exacerbate the negative consequences of climate variability. There is considerable scope and incentive, therefore, to invest in irrigation and water management practices to mitigate the adverse effects of both climate variability and climate change on Zambia's economic development.

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Appendix A: Description of the hydro-crop (HC) model

Quantitative information on crop yield responses to water deficiency is crucial for evaluating the economic impacts of climate variability and change on agricultural production. A semi-empirical model was developed that includes two modules. The first module simulates soil water balance in crop root zone to derive actual evapotranspiration (ET). The second module estimates crop yield responses to water deficits using an empirical crop water production function that takes into account growing stage-specific crop sensitivity to water stress. Together these two modules form the integrated 'hydro-crop' model that is used in this study.

The soil water balance module regards crop root zone as a bucket with water flowing in through rainfall, and irrigation if applicable, and water leaking away as ET, runoff and deep percolation. The first step in the soil water balance is to estimate crop water requirements, which are normally expressed as a rate of potential ET. The potential ET for a particular crop is estimated using potential ET of a reference crop, usually alfalfa, and a calibrated crop coefficient which converts the reference ET to potential ET of the crop, under given climatic conditions. With rainfall and potential ET, the soil water balance module calculates actual ET and water surplus using actual soil water content and available water capacity (AWC) in crop root zone. If the soil water content is above a threshold level of AWC then actual ET takes place at the potential rate. But if it is not, then actual ET is stressed by soil moisture. Surface runoff and deep percolation occur if the estimated end-of-period soil water content exceeds AWC. The soil water balance module runs continuously and produces actual ET, which is then used in the crop water production function to estimate crop yield reduction resulting from water deficit. As daily climate data was not available, the soil water balance simulations were done at monthly intervals using long-term monthly data.

The second module in the hydro-crop model was a nonlinear Jensen crop water production model, which was used to estimate crop yield responses to water using monthly data of actual and potential ET values during crop growing season. The Jensen function is an empirical water production function but its advantage over the FAO crop yield response model is that the Jensen function can take into account growth stage-specific sensitivity to water of crops. By contrast, the FAO model only considers water deficits for the entire growing season and thus cannot capture monthly climate variations and crop yield sensitivities to water. We compared observed yields in the five agro-ecological zones in Zambia with simulations from both Jensen and FAO models and found that the Jensen function outperformed the FAO model for our purposes since crop losses in Zambia are particularly sensitive to seasonal water deficits, especially in major drought years. For each crop, water sensitivity index values in the Jensen crop water production function were estimated based on stage-specific FAO yield response factors using OLS regression. These were then mapped to each month in crops' growing periods using a cumulative sensitivity index method.

For all crops and all agro-ecological zones in Zambia, their hydro-crop model simulations were done based on observed meteorological data provided by the Zambia Department of Meteorology. This part of the study used monthly climate data from 1975 to 2007 at thirty meteorological stations. Rainfall and calculated potential ET were aggregated to the five agro-ecological zones based on the estimated influencing domain of each station. The latter was based on the area of each Thiessen polygon within a zone and the areas of other Thiessen polygons within the same agro-ecological zone.

Appendix B: Specification of the hydrological and crop production models

Model	Parameter		Unit
Crop Water Requirement	K_c	Crop coefficient	-
	γ	Psychrometric constant	kPa °C^{-1}
	K_{Rs}	Radiation adjustment coefficient	-
Soil Water Balance	S_{max}	Maximum tension water capacity in root zone	mm m^{-1}
	θ_f	Field capacity	mm m^{-1}
	θ_w	Wilting point	mm m^{-1}
	Z_r	Root zone depth	m
	p	Fraction of active tension water capacity in root zone below which crop begin to experience stress	-
Crop Water Production Function	Ymax	Maximum yield without water stress	t ha^{-1}
	Ky	yield response factor	-
	λ_t	Crop water sensitivity index	-
Model	**Variable**		**Unit**
Crop Water Requirement	ETo	Reference evapotranspiration	mm
	PET	Crop potential evapotranspiration	mm
	Rs	Incoming solar radiation	MJ m^{-2} day^{-1}
	R_n	Net radiation at the crop surface	MJ m^{-2} day^{-1}
	R_a	Extraterrestrial radiation	MJ m^{-2} day^{-1}
	G	Soil heat flux density	MJ m^{-2} day^{-1}
	T	Mean daily air temperature at 2 m height	°C
	T_{max}	Maximum daily air temperature at 2 m height	°C
	T_{max}	Minimum daily air temperature at 2 m height	°C
	e_s	Saturation vapour pressure	kPa
	Δ	slope vapour pressure curve	kPa °C^{-1}
	u_2	wind speed at 2 m height	m s^{-1}
Soil Water Balance	P	Rainfall	mm
	AET*	Predicted actual crop evapotranspiration	mm
	AET	Adjusted actual crop evapotranspiration	mm
	S	Soil water content in root zone	mm
Crop Water Production Function	Ya	Actual crop yield	t ha^{-1}

Model	Equation	Equation No.	Notes
Crop Water Requirement	$ET_o = \dfrac{0.408\Delta(R_n - G) + \gamma \dfrac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$	2.1	FAO Penman-Monteith equation (Allen et al., 1998) for calculating reference evapotranspiration
	$R_s = K_{Rs} \cdot (T_{\max} - T_{\min})^{0.5} \cdot R_a$	2.2	Hargreaves' radiation formula as recommended by Allen et al. (1998) when radiation data is not available
	$PET_t = K_c \cdot ET_o$	2.3	Crop potential evapotranspiration Allen et al. (1998)
Soil Water Balance	$S_{\max} = (\theta_f - \theta_w)Z_r$	2.4	Active tension water capacity in root zoon
	$AET_t^* = \begin{cases} \dfrac{S_{t-1} + P_t}{p \cdot S_{\max}} \cdot PET_t\ , & S_{t-1} + P_t < p \cdot S_{\max} \\ PET_t\ , & S_{t-1} + P_t \geq p \cdot S_{\max} \end{cases}$	2.5	Predicted actual crop evapotranspiration
	$AET_t = \min\left\langle AET_t^*\ ,\ S_{t-1} + P_t \right\rangle$	2.6	Adjusted crop actual evapotranspiration
	$S_t = \begin{cases} S_{t-1} + P_t - AET_t\ , & S_{t-1} + P_t - AET < S_{\max} \\ S_{\max}\ , & S_{t-1} + P_t - AET \geq S_{\max} \end{cases}$	2.7	End of period soil water content
Crop Water Production Function	$Y_a = Y_{\max} \left[1 - K_y \cdot \left(1 - \dfrac{\sum_t AET_t}{\sum_t PET_t} \right) \right], \qquad t \in T$	2.8	FAO yield response function (Doorenbos and Kassam, 1979)
	$Y_a = Y_{\max} \cdot \prod_{t \in T} \left(\dfrac{AET_t}{PET_t} \right)^{\lambda_t}$	2.9	Jensen crop water production function (Jensen, 1968)

Appendix C: Description of the economywide model and the Zambian economy

A dynamic computable general equilibrium (DCGE) model of Zambia is developed to examine the economywide growth and poverty impacts of the climate variability predicted by the hydrological model. In order to better understand how the output of a hydrological model will become inputs of a DCGE model and how the climate variability affects the economy directly and indirectly, we provide a brief discussion about what is the DCGE model and what the model can do in this study in this section. In general, a CGE model is a multi-sector general equilibrium model, while the model developed for this study also contains detailed information on sub-national production and employment; in addition to national levels of domestic and international trade. The households and their income sources are also considered at the sub-national level, which allows the model to be used for welfare and poverty analysis at the both national, sub-national level according to different types of household groups. Below we discuss the structure of the model in detail with reference to the Zambian economy. We then turn to describe how the DCGE model to incorporate the output of the hydrological model such that the model can be used in this study.

Production and Employment

The DCGE model of Zambia contains 34 production sectors that produce 34 commodities. Among the 34 sectors 17 belong to the agricultural sector, 9 are industrial and 8 are service sectors (see Table C1 for the list of sectors). Agricultural crops fall into four broad groups: (i) cereals, including maize, sorghum and millet, and other cereals (i.e., wheat and rice); (ii) root crops (e.g., cassava, Irish potatoes, and sweet potatoes); (iii) other food crops, including pulses, groundnuts, other oilseeds, vegetables, and fruits; and (iv) higher-value export-oriented crops, including cotton, sugar, tobacco, and other export crops (e.g., soybeans). The CGE model also identifies three livestock subsectors, namely cattle, poultry, and other livestock, such as sheep, goats and pigs. The two remaining agricultural sub-sectors are forestry and fisheries. Together, these agricultural subsectors account for 22 percent of gross domestic product (GDP) and 16 percent of exports (see Table C2).

Table C1: Sectors in the CGE model

		Irrigated	Regional disaggregation
	Agricultural sub-sectors		
	Cereals		
1	Maize	No	5 zones, urban & large-scale
2	Sorghum & millet	No	5 zones, urban & large-scale
3	Other cereals (i.e., wheat and rice)	Yes	5 zones, urban & large-scale
4	Root crops (incl. cassava, sweet and Irish potatoes)	No	5 zones, urban & large-scale
	Other food crops		
5	Pulses & oils (incl. beans)	No	5 zones, urban & large-scale
6	Groundnuts	No	5 zones, urban & large-scale
7	Vegetables	No	5 zones, urban & large-scale
8	Fruits	No	5 zones, urban & large-scale
	High-value export-oriented crops		
9	Cotton	No	5 zones, urban & large-scale
10	Sugarcane	Yes	5 zones, urban & large-scale
11	Tobacco	No	5 zones, urban & large-scale
12	Other crops (mainly soybeans)	Yes	5 zones, urban & large-scale
	Livestock		
13	Cattle		5 zones & urban
14	Poultry		5 zones & urban
15	Other livestock (incl. goats, sheep and pigs)		5 zones & urban
16	Fisheries		5 zones
17	Forestry		National
	Industrial sub-sectors		
18	Mining		National
19	Food processing, beverages & tobacco		National
20	Textiles & clothing		National
21	Wood & paper products		National
22	Chemicals & rubber products		National
23	Machinery & equipment (incl. vehicles)		National
24	Other manufacturing (incl. furniture)		National
25	Electricity & water		National
26	Construction		National
	Service sub-sectors		
27	Trade services		National
28	Hotels & catering		National
29	Transport & communication services		National
30	Financial, business & real estate services		National
31	Government administration		National
32	Education services		National
33	Health services		National
34	Community & other services		National

Source: 2006 Social Accounting Matrix of Zambia

Table C2: National production and trade structure of the Zambian economy

	Share of total (%)			Trade intensity	
	GDP	Exports	Imports	Exports	Imports
Total GDP	100.00	100.00	100.00	19.85	21.67
Agriculture	21.94	15.75	5.65	15.54	6.63
Cereals	9.48	4.06	4.13	9.13	9.78
Maize	8.78	3.91	2.28	9.42	6.04
Sorghum & millet	0.43		0.08		5.20
Other cereals	0.27	0.15	1.77	11.01	60.85
Root crops	0.67	0.56	0.11	24.08	6.24
Other food crops	4.33	0.02	0.65	0.12	3.93
Pulses & oils	0.40	0.02	0.14	1.27	8.82
Groundnuts	1.53				
Vegetables	1.73				
Fruits	0.68		0.50		18.40
Export-oriented crops	3.46	9.67	0.33	64.60	6.43
Cotton	1.14	4.90	0.13	84.61	13.46
Sugarcane	1.61	2.46		42.03	
Tobacco	0.46	1.20		54.01	
Other crops	0.25	1.12	0.20	100.00	100.00
Livestock	2.26	0.17	0.20	1.29	1.78
Cattle	0.88		0.19		4.94
Poultry	0.71		0.00		0.07
Other livestock	0.68	0.17	0.01	5.47	0.38
Fisheries	0.93	0.94		21.60	
Forestry	0.80	0.32	0.23	7.40	6.05
Mining	7.10	69.06		98.89	
Manufacturing	11.97	5.01	69.25	5.86	49.55
Food processing	6.46	1.86	3.15	4.57	8.44
Textiles & clothing	1.75		5.93		36.99
Wood & paper products	1.14	2.05	1.65	24.13	22.06
Chemicals & rubber products	1.08	1.11	23.51	8.79	69.01
Machinery & equipment	1.26		33.04		79.78
Other manufacturing	0.28		1.97		55.29
Electricity & water	2.95				
Construction	5.73				
Services	50.31	10.18	25.09	5.09	12.29
Trade services	17.36				
Hotels & catering	2.94	5.98		47.86	
Transport & communication	4.78	4.20	21.52	19.59	56.97
Financial and business services	4.65		3.57		17.55
Government administration	8.07				
Education services	8.90				
Health services	2.97				
Community & other services	0.63				

Source: 2006 Social Accounting Matrix of Zambia
Note: Export-intensity is the share of exports in domestic output, and import-intensity is the share of imports in domestic supply.

Zambia's industrial sectors are of similar size to agriculture, accounting for 28 percent of GDP. However, most of the manufacturing sector is linked to agriculture, such as food processing, textiles and wood products. This is because most agricultural commodities are not only exported or consumed by households in Zambia, but are also used as inputs in upstream processing activities, which together generate an additional 9 percent of GDP. However, while agriculture and related sectors dominate GDP, it is copper that is most important for exports, generating 70 percent of total export earnings. Almost all of mining production is exported, reflecting the relatively weak linkages between this sector and the rest of the economy. The CGE model captures Zambia's sectoral structure and its intersectoral linkages by drawing on the information contained in the 2005 social accounting matrix (SAM).[24]

Beyond its sectoral detail, the CGE model also captures sub-national or spatial heterogeneity in production patterns. Based on district-level data from the 2004/05 Crop Forecasting Survey (CFS04/05), agricultural production is disaggregated across the five agro-climatic regions similar as in the hydrological model (i.e., Zambia's four agro-ecological zones, with Zone 2a further divided into western (Zone 2a1) and eastern (Zone 2a2) sub-zones). Moreover, to capture the unique circumstances of urban agriculture, agricultural production for the main urban centers is identified separately based on household production information from the 2004/05 Living Standards Monitoring Survey (LCMS4).[25] Thus, there are six sub-national regions identified in the model: five rural and one urban. Finally, a seventh group comprising large-scale farmers is separated from small/medium-scale producers that are zonal specific. The different cropping patterns of these farm groups are shown in Table C3.

Maize is the main crop in Zambia with 42 percent of harvested land allocated to maize production. Scale of production is a key distinguishing feature. While large-scale farmers represent only 8 percent of total maize land they produce 22 percent of maize in the country.[26] Since there was virtually no irrigated maize production in the country, average yields for large-scale farmers are high for dry-land production at over six tons per hectare in 2005, a year with relatively good rainfall. By contrast, small-scale farmers, who account for four-fifths of maize production, achieve much lower yields of around two tons per hectare. Agro-ecological conditions across zones are also an important factor to determine the yield level. Smallholder maize yields range from around 1.5 tons per hectare in the southern and western regions (i.e., Zones 1 and 2b) to 2.4 tons per hectare in the central region (i.e., Zone 2a1). Other factors also serve to concentrate maize production within specific regions. For instance, four-fifths of large-scale maize production takes place in Zone 2a1, where not only are agro-ecological conditions more favorable in a normal rainfall year, but where farmers have better access to urban centers. Finally, urban-based farmers are also an important part of Zambia's agricultural system. Around a quarter of urban households are engaged in agricultural production, primarily maize cropping and livestock. Thus, in summary, while Zone 3 is the largest region in terms of cultivated land size, it is the central Zone 2a1 that dominates maize production in Zambia due to higher maize yields and a concentration of large-scale and urban farmers in this region.

[24] The 2005 Zambia SAM is an updated and aggregated version of the 2004 SAM used in Thurlow et al. (2008).

[25] Metropolitan centers are urban areas in these districts: Kabwe (Central); Chingola, Chililabombwe, Kitwe, Kalulushi, Lufwanyama, Mufulira and Ndola (Copperbelt); Lusaka (Lusaka); and Livingstone (Southern).

[26] Large-scale farmers in Zambia are defined as having more than 20 hectares of land.

Table C3: National production and trade structure of the Zambian economy

	Share of total (%)			Trade intensity	
	GDP	Exports	Imports	Exports	Imports
Total GDP	100.00	100.00	100.00	19.85	21.67
Agriculture	21.94	15.75	5.65	15.54	6.63
Cereals	9.48	4.06	4.13	9.13	9.78
Maize	8.78	3.91	2.28	9.42	6.04
Sorghum & millet	0.43		0.08		5.20
Other cereals	0.27	0.15	1.77	11.01	60.85
Root crops	0.67	0.56	0.11	24.08	6.24
Other food crops	4.33	0.02	0.65	0.12	3.93
Pulses & oils	0.40	0.02	0.14	1.27	8.82
Groundnuts	1.53				
Vegetables	1.73				
Fruits	0.68		0.50		18.40
Export-oriented crops	3.46	9.67	0.33	64.60	6.43
Cotton	1.14	4.90	0.13	84.61	13.46
Sugarcane	1.61	2.46		42.03	
Tobacco	0.46	1.20		54.01	
Other crops	0.25	1.12	0.20	100.00	100.00
Livestock	2.26	0.17	0.20	1.29	1.78
Cattle	0.88		0.19		4.94
Poultry	0.71		0.00		0.07
Other livestock	0.68	0.17	0.01	5.47	0.38
Fisheries	0.93	0.94		21.60	
Forestry	0.80	0.32	0.23	7.40	6.05
Mining	7.10	69.06		98.89	
Manufacturing	11.97	5.01	69.25	5.86	49.55
Food processing	6.46	1.86	3.15	4.57	8.44
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Chemicals & rubber products	1.08	1.11	23.51	8.79	69.01
Machinery & equipment	1.26		33.04		79.78
Other manufacturing	0.28		1.97		55.29
Electricity & water	2.95				
Construction	5.73				
Services	50.31	10.18	25.09	5.09	12.29
Trade services	17.36				
Hotels & catering	2.94	5.98		47.86	
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Government administration	8.07				
Education services	8.90				
Health services	2.97				
Community & other services	0.63				

Source: 2006 Social Accounting Matrix of Zambia

Note: Export-intensity is the share of exports in domestic output, and import-intensity is the share of imports in domestic supply.

The remaining cereal groups differ sharply in their production structure and technology. On the one hand, sorghum and millet is overwhelmingly a smallholder crop and is particularly important as a drought-tolerant staple in Zambia's drier southern region (i.e., Zone 1). On the other hand, wheat (which is aggregated into the 'other cereals' sub-sector in the model) is grown entirely under irrigation and by large-scale farmers in the southern and central regions of the country (i.e., Zones 1 and 2a1). Some smallholders grow rice (also included in 'other cereals'), especially in the northern region, but relatively little land is allocated to this crop. As such, the 'other cereals' as a crop group is treated as being entirely irrigated. Finally, as with maize, the regional concentration of wheat production reflects differences in agro-ecological conditions and market access, and further justifies the division of Zone 2a into eastern and western sub-zones in our study.

The remaining food crops are distributed across the country roughly in proportion to each zone's total land area. The only exception is root crops. Although cassava and potatoes are grown in all zones, they are particularly important in the eastern and northern regions (i.e., Zones 2a2 and 3), where an even larger amount of land is allocated to root crops than to maize. Finally, Zambia's export crops are also concentrated in some specific zones. Cotton is grown in the eastern and central regions (i.e., Zone 2a) under smallholder out-grower schemes, while tobacco is almost exclusively grown in the eastern region (Zone 2a2) by both small and large-scale farmers. Both of these crops are grown on dry lands. By contrast, sugarcane and soybeans (included in 'other crops' sub-sector in the model) are grown under irrigation by large-scale farmers in the center of the country (i.e., Zone 2a2). Finally, livestock is an important agricultural sub-sector, generating ten percent of agricultural GDP. Three quarters of livestock GDP is in Zones 1 and 2a1, where cattle herds and poultry stocks are largest and where they are an important source of rural incomes.

The DCGE model captures differences in production technologies, such as the higher labor-intensity of agriculture and capital-intensity of industry. Here the model identifies eight factors of production: three types of labor (unskilled workers, skilled workers, and family farm labor); three kinds of capital (agricultural, mining and nonagricultural); and two kinds of agricultural assets (land and livestock stocks). Skilled and unskilled workers, who are assumed to be fully employed and are able to migrate across regions and sectors in response to changes in labor demand. However, family farm labor and agricultural capital can only be allocated across farm activities within each zone. Since we are interested in capturing the impact of rainfall variation shocks, we assume that the allocation of land, livestock stocks, and nonagricultural capital across different production activities is constant, so that these factors are immobile across sectors and earn sector-specific returns. Producers in each zone and sector employ the eight different factors in varying intensities in order to maximize profits under constant returns to scale, with the choice between factors governed by a constant elasticity of substitution (CES) function. Composite factors are then combined with intermediate inputs under a Leontief specification with fixed input-output coefficients taken from the input-output table underlying the 2005 Zambia SAM.

Domestic and International Trade

Table C2 also showed the structure of foreign trade in Zambia. From this it was clear that the country is heavily dependent on mining exports. However, there was considerable growth in agricultural exports during the 1990s, especially from cotton and sugarcane. Zambia is both an importer and exporter of maize, with the net trade position varying from year to year and depending on the rainfall situation. Most large-scale wheat production in the country is for the domestic market, but wheat imports are still needed, though the level is relatively low. Imports are actually dominated by nonagricultural products. Chemicals (including fuels) and machinery (including vehicles and equipment) are high import-intensive sub-sectors. Thus, despite being landlocked, Zambia is heavily reliant on international trade, which in turn is concentrated within a narrow range of commodities for both exports and imports.

The CGE model captures these linkages with the rest of the world through exports and imports. Producers in each region supply their output to a national commodity market, where they are exported, sold domestically, and/or combined with imported goods. Substitution possibilities exist between production for domestic and foreign markets based on a constant elasticity of transformation (CET) function. Profit maximization drives producers to sell in those markets where they can achieve the highest returns. These returns are based on domestic and export prices (where the latter is determined by the world price times the exchange rate). Substitution possibilities also exist between imported and domestic goods under a CES Armington specification. The ratio of imports to domestic goods is determined by the cost minimizing decision-making of domestic demanders based on the relative prices of imports and domestic goods (both of which include relevant taxes).

Under the small-country assumption, Zambia faces perfectly elastic foreign demand/supply from the world at fixed world prices. However, with imperfect substitution between domestically produced and consumed goods and export or import goods, prices for all commodities either produced or sold in domestic markets are endogenous. While an integrated domestic market is assumed, agricultural products produced from different zones are imperfectly substitutable.

Household Incomes and Poverty

The CGE model distinguishes between various representative household groups. While representative households are zone-specific, they are further disaggregated into rural and urban areas. Rural households within each zone are further distinguished into three groups: small farm, large-scale farm and non-farm households. Urban and metropolitan households are disaggregated into two groups depending on whether they engage in agricultural production. Each of the 27 representative households in the CGE model is an aggregation of individual households captured in the 2004/05 household survey (LCMS4). Households in the model receive income from different factors employed in different production processes. They then pay taxes to government and/or receive transfers from the government. A part of household incomes come from abroad as remittance receipts. As the dynamics of the model is recursive, fixed saving rates are assumed for each representative households. The income allocated to consumption of different commodities is derived from maximizing a Stone-Geary utility function, which results in a linear expenditure system (LES) of demand.[27]

[27] The LES specification identifies a portion of consumption for subsistence (i.e., income and price independent). The remaining consumption quantities are sensitive to price and income changes. Commodity income elasticities

Table C4 provides income and poverty statistics for the representative aggregate household groups in the model. Poverty is extremely high in Zambia, with 67.9 percent of the population of 11 million falling below the official poverty line of around US$300 per person per year. Poverty is highest in rural areas, where 61 percent of the population resides. As a result, more than 70 percent of Zambia's poor population lives in rural areas where, on average, they derive about 80 percent of their incomes from agriculture.

Poverty rates are high in all of the five rural zones identified in the CGE model. However, there is some variation, with poverty lowest in Zone 2a2 and highest in Zone 2b. The former includes many cotton farmers, whose rising incomes were instrumental in reducing rural poverty in Zambia during the mid-1990s. However, while per capita incomes are highest in Zone 2a1, poverty rates in this zone are still high at 79 percent. This reflects Zambia's high income inequality, with the relatively few households who are living closest to large urban centers and major transport routes having considerably lower poverty incidence.[28] Finally, Table C4 shows average farm plot sizes for different household groups, which vary greatly across zones. Farm plots are smallest in urban areas and in Zone 2b and largest in the more sparsely populated Zone 2a2. The CGE model captures these differences in household income patterns, as well as the differences in the way their incomes are spent.

To assess the impact of alternative rainfall scenarios on household poverty, the CGE model needs to link with a micro-simulation model in which each sample household in the 2004/05 LCMS is included. These sample households are further linked to their corresponding representative household in the CGE model on the consumption-side. In this formulation, changes in representative households' consumption for individual commodities (resulting from income and commodity price changes) in the CGE model, are passed down to their corresponding households in the micros-simulation model, where total consumption expenditures in real terms are recalculated. This new level of per capita expenditure for each survey household is compared to the official poverty line, and standard poverty measures are recalculated.

Model Closure and Dynamics

The CGE model captures the workings of the government, which receives revenues from imposing activity, sales and direct taxes and import tariffs, and then makes transfers to households and the rest of the world. The government also purchases commodities in the form of government consumption or recurrent expenditure, and the remaining income of government is (dis)saved. All savings from households, government and capital inflows from abroad (foreign savings) form a savings pool from which investment is financed.

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are taken from Thurlow et al. (forthcoming) and allow for differences between marginal and average budget shares.

[28] See Thurlow and Wobst (2006) on the role of remoteness in determining rural poverty in Zambia.

Table C4: Household income and poverty characteristics

	Population (1000)		Households (1000)		Per capita expenditure		Poverty rate (%)	Average size and allocation of crop land (ha)				
	Total	Poor	Total	Size	Kw 1000	$US		All crops	Maize	Roots	Other foods	Export crops
All households	10,986	7,461	2,089	5.26	1,861	417	67.9	-	-	-	-	-
Urban households	4,298	2,271	814	5.28	3,242	726	52.8	-	-	-	-	-
Non-farm	3,075	1,484	619	4.97	3,625	812	48.3	-	-	-	-	
Farm	1,223	793	195	6.26	2,281	511	64.8	0.25	0.17	0.00	0.08	0.00
Rural households	6,687	5,192	1,275	5.24	974	218	77.6	-	-	-	-	-
Non-farm	722	540	171	4.22	1,320	296	74.8	-	-	-	-	-
Farm	5,965	4,653	1,104	5.40	932	209	78.0	-	-	-	-	-
Zone I	814	657	144	5.64	754	169	80.8	1.18	0.63	0.08	0.36	0.11
Zone IIa:1	1,258	991	215	5.86	1,564	350	78.8	1.26	0.64	0.09	0.24	0.30
Zone IIa:2	1,074	790	198	5.42	859	192	73.6	1.52	0.68	0.07	0.36	0.41
Zone IIb	383	321	75	5.08	648	145	84.0	0.69	0.18	0.33	0.15	0.02
Zone III	2,437	1,892	471	5.17	793	178	77.6	1.11	0.34	0.41	0.34	0.01

Source: 2006 Social Accounting Matrix of Zambia and 2004/05 Living Conditions Monitoring Survey (LCMS4)

The model contains three macroeconomic accounts: (i) the government account; (ii) savings-investment account; and (iii) current account. In order to bring about balance between macroeconomic accounts, it is necessary to specify a set of 'macroclosure' rules, which provide a mechanism through which macroeconomic balance can be achieved. Following a Solow growth model, a savings-driven closure was assumed in order to balance the savings-investment account. Under this closure, households' savings rates are held fixed and investment adjusts endogenously to equalize investment and savings in equilibrium. In the government account, direct tax rates on households and capital are assumed to remain unchanged, with government revenues and expenditures balanced through changes in public spending and the fiscal deficit. Finally, for the current account we assumed that foreign savings (i.e., foreign capital inflows) are constant. The exchange rate was chosen as the model's numéraire**.**

Our DCGE model is a 'recursive' dynamic one, which means that there does not exist any intertemporal decision making for households, both as consumers and producers. Thus, the stock variables need to be updated between periods. While growth in population, and hence labor supply and agricultural land expansion, is exogenously determined between periods, the capital accumulation is endogenously constrained by the level of investment in previous time periods. Once the new capital is formed from previous periods' investment, it becomes part of the capital stock that is allocated to different sectors according to the sectoral level of capital returns. This implies that sectors with above-average returns in the previous period receive a larger share of the new capital stock in the current period.

Appendix D: Specification of the computable general equilibrium model

Symbol	Explanation	Symbol	Explanation
Sets			
$a \in A$	Activities	$c \in CMN(\subset C)$	Commodities not in *CM*
$a \in ALEO(\subset A)$	Activities with a Leontief function at the top of the technology nest	$c \in CT(\subset C)$	Transaction service commodities
$c \in C$	Commodities	$c \in CX(\subset C)$	Commodities with domestic production
$c \in CD(\subset C)$	Commodities with domestic sales of domestic output	$f \in F$	Factors
$c \in CDN(\subset C)$	Commodities not in *CD*	$i \in INS$	Institutions (domestic and rest of world)
$c \in CE(\subset C)$	Exported commodities	$i \in INSD(\subset INS)$	Domestic institutions
$c \in CEN(\subset C)$	Commodities not in *CE*	$i \in INSDNG(\subset INSD)$	Domestic non-government institutions
$c \in CM(\subset C)$	Aggregate imported commodities	$h \in H(\subset INSDNG)$	Households
Parameters			
$cwts_c$	Weight of commodity c in the CPI	$qdst_c$	Quantity of stock change
$dwts_c$	Weight of commodity c in the producer price index	$\overline{qg}_c$	Base-year quantity of government demand
ica_{ca}	Quantity of c as intermediate input per unit of activity a	$\overline{qinv}_c$	Base-year quantity of private investment demand
$icd_{cc'}$	Quantity of commodity c as trade input per unit of c' produced and sold domestically	$shif_{if}$	Share for domestic institution i in income of factor f
$ice_{cc'}$	Quantity of commodity c as trade input per exported unit	$shii_{ii'}$	Share of net income of i' to i
$icm_{cc'}$	Quantity of commodity c as trade input per imported unit of c'	ta_a	Tax rate for activity a
$inta_a$	Quantity of aggregate intermediate input per activity unit	$\overline{tins}_i$	Exogenous direct tax rate for domestic institution i
iva_a	Quantity of aggregate intermediate input per activity unit	$tins01_i$	0-1 parameter with 1 for institutions with potentially flexed direct tax rates
$\overline{mps}_i$	Base savings rate for domestic institution i	tm_c	Import tariff rate
$mps01_i$	0-1 parameter with 1 for institutions with potentially flexed direct tax rates	tq_c	Rate of sales tax
pwe_c	Export price (foreign currency)	$trnsfr_{i\,f}$	Transfer from factor f to institution i
pwm_c	Import price (foreign currency)		

Symbol	Explanation	Symbol	Explanation
Greek Symbols			
α_a^a	Efficiency parameter in the CES activity function	δ_{cr}^t	CET function share parameter
α_a^{va}	Efficiency parameter in the CES value-added function	δ_{fa}^{va}	CES value-added function share parameter for factor *f* in activity *a*
α_c^{ac}	Shift parameter for domestic commodity aggregation function	γ_{ch}^m	Subsistence consumption of marketed commodity c for household h
α_c^q	Armington function shift parameter	θ_{ac}	Yield of output c per unit of activity a
α_c^t	CET function shift parameter	ρ_a^a	CES production function exponent
β^a	Capital sectoral mobility factor	ρ_a^{va}	CES value-added function exponent
β_{ch}^m	Marginal share of consumption spending on marketed commodity c for household h	ρ_c^{ac}	Domestic commodity aggregation function exponent
δ_a^a	CES activity function share parameter	ρ_c^q	Armington function exponent
δ_{ac}^{ac}	Share parameter for domestic commodity aggregation function	ρ_c^t	CET function exponent
δ_{cr}^q	Armington function share parameter	η_{fat}^a	Sector share of new capital
υ_f	Capital depreciation rate		
Exogenous Variables			
$\overline{CPI}$	Consumer price index	$\overline{MPSADJ}$	Savings rate scaling factor (= 0 for base)
$\overline{DTINS}$	Change in domestic institution tax share (= 0 for base; exogenous variable)	$\overline{QFS}_f$	Quantity supplied of factor
$\overline{FSAV}$	Foreign savings (FCU)	$\overline{TINSADJ}$	Direct tax scaling factor (= 0 for base; exogenous variable)
$\overline{GADJ}$	Government consumption adjustment factor	$\overline{WFDIST}_{fa}$	Wage distortion factor for factor f in activity a
$\overline{IADJ}$	Investment adjustment factor		
Endogenous Variables			
AWF_{ft}^a	Average capital rental rate in time period t	QG_c	Government consumption demand for commodity
$DMPS$	Change in domestic institution savings rates (= 0 for base; exogenous variable)	QH_{ch}	Quantity consumed of commodity c by household h
DPI	Producer price index for domestically marketed output	QHA_{ach}	Quantity of household home consumption
EG	Government expenditures	$QINTA_a$	Quantity of aggregate intermediate input
EH_h	Consumption spending for household	$QINT_{ca}$	Quantity of commodity c as intermediate input to activity a
EXR	Exchange rate (LCU per unit of FCU)	$QINV_c$	Quantity of investment demand
$GSAV$	Government savings	QM_{cr}	Quantity of imports of commodity c
QF_{fa}	Quantity of factor demand		

Symbol	Explanation	Symbol	Explanation
Endogenous Variables Continued			
MPS_i	Marginal propensity to save for domestic non-government institution (exogenous variable)	QQ_c	Quantity of goods supplied to domestic market (composite supply)
PA_a	Activity price (unit gross revenue)	QT_c	Quantity of commodity demanded as trade input
PDD_c	Demand price for commodity produced and sold domestically	QVA_a	Quantity of (aggregate) value-added
PDS_c	Supply price for commodity produced and sold domestically	QX_c	Aggregated quantity of domestic output of commodity
PE_{cr}	Export price (domestic currency)	$QXAC_{ac}$	Quantity of output of commodity c from activity a
$PINTA_a$	Aggregate intermediate input price for activity a	RWF_f	Real average factor price
PK_{ft}	Unit price of capital in time period t	$TABS$	Total nominal absorption
PM_{cr}	Import price (domestic currency)	$TINS_i$	Direct tax rate for institution i (i $\in$ INSDNG)
PQ_c	Composite commodity price	$TRII_{ii'}$	Transfers from institution i' to i (both in the set INSDNG)
PVA_a	Value-added price (factor income per unit of activity)	WF_f	Average price of factor
PX_c	Aggregate producer price for commodity	YF_f	Income of factor f
$PXAC_{ac}$	Producer price of commodity c for activity a	YG	Government revenue
QA_a	Quantity (level) of activity	YI_i	Income of domestic non-government institution
QD_c	Quantity sold domestically of domestic output	YIF_{if}	Income to domestic institution i from factor f
QE_{cr}	Quantity of exports	ΔK^{a}_{fat}	Quantity of new capital by activity a for time period t

Production and Price Equations	
$QINT_{c\,a} = ica_{c\,a} \cdot QINTA_a$	(1)
$PINTA_a = \sum_{c \in C} PQ_c \cdot ica_{ca}$	(2)
$QVA_a = \alpha_a^{va} \cdot \left(\sum_{f \in F} \delta_{f\,a}^{va} \cdot \alpha_{f\,a}^{vaf} \cdot QF_{f\,a}^{\;-\rho_a^{va}} \right)^{-\frac{1}{\rho_a^{va}}}$	(3)
$W_f \cdot \overline{WFDIST}_{fa} = PVA_a \cdot QVA_a \cdot \left(\sum_{f \in F'} \delta_{f\,a}^{va} \cdot \alpha_{f\,a}^{vaf} \cdot QF_{f\,a}^{\;-\rho_a^{va}} \right)^{-1} \cdot \delta_{f\,a}^{va} \cdot \alpha_{f\,a}^{vaf} \cdot QF_{f\,a}^{\;-\rho_a^{va}-1}$	(4)
$QF_{f\,a} = \alpha_{f\,a}^{van} \cdot \left(\sum_{f' \in F} \delta_{f\,f'a}^{van} \cdot QF_{f'a}^{\;-\rho_{f\,a}^{van}} \right)^{-\frac{1}{\rho_{f\,a}^{van}}}$	(5)
$W_{f'} \cdot WFDIST_{f'a} = W_f \cdot WFDIST_{f\,a} \cdot QF_{f\,a} \cdot \left(\sum_{f'' \in F} \delta_{f\,f''a}^{van} \cdot QF_{f''a}^{\;-\rho_{f\,a}^{van}} \right)^{-1} \cdot \delta_{f\,f'a}^{van} \cdot QF_{f'a}^{\;-\rho_{f\,a}^{van}-1}$	(6)
$QVA_a = iva_a \cdot QA_a$	(7)
$QINTA_a = inta_a \cdot QA_a$	(8)
$PA_a \cdot (1 - ta_a) \cdot QA_a = PVA_a \cdot QVA_a + PINTA_a \cdot QINTA_a$	(9)
$QXAC_{a\,c} = \theta_{a\,c} \cdot QA_a$	(10)
$PA_a = \sum_{c \in C} PXAC_{ac} \cdot \theta_{ac}$	(11)
$QX_c = \alpha_c^{ac} \cdot \left(\sum_{a \in A} \delta_{a\,c}^{ac} \cdot QXAC_{a\,c}^{\;-\rho_c^{ac}} \right)^{-\frac{1}{\rho_c^{ac}-1}}$	(12)
$PXAC_{a\,c} = PX_c \cdot QX_c \left(\sum_{a \in A'} \delta_{a\,c}^{ac} \cdot QXAC_{a\,c}^{-\rho_c^{ac}} \right)^{-1} \cdot \delta_{a\,c}^{ac} \cdot QXAC_{a\,c}^{-\rho_c^{ac}-1}$	(13)
$PE_{cr} = pwe_{cr} \cdot EXR - \sum_{c' \in CT} PQ_c \cdot ice_{c'c}$	(14)
$QX_c = \alpha_c^t \cdot \left(\sum_r \delta_{cr}^t \cdot QE_{cr}^{\rho_c^t} + (1 - \sum_r \delta_{cr}^t) \cdot QD_c^{\rho_c^t} \right)^{\frac{1}{\rho_c^t}}$	(15)
$\frac{QE_{cr}}{QD_c} = \left(\frac{PE_{cr}}{PDS_c} \cdot \frac{1 - \sum_r \delta_{cr}^t}{\delta_c^t} \right)^{\frac{1}{\rho_c^t - 1}}$	(16)

$$QX_c = QD_c + \sum_r QE_{cr}$$ (17)

$$PX_c \cdot QX_c = PDS_c \cdot QD_c + \sum_r PE_{cr} \cdot QE_{cr}$$ (18)

$$PDD_c = PDS_c + \sum_{c' \in CT} PQ_{c'} \cdot icd_{c'c}$$ (19)

$$PM_{cr} = pwm_{cr} \cdot (1 + tm_{cr}) \cdot EXR + \sum_{c' \in CT} PQ_{c'} \cdot icm_{c'c}$$ (20)

$$QQ_c = \alpha_c^q \cdot \left(\sum_r \delta_{cr}^q \cdot QM_{cr}^{-\rho_c^q} + (1 - \sum_r \delta_{cr}^q) \cdot QD_c^{-\rho_c^q} \right)^{-\frac{1}{\rho_c^q}}$$ (21)

$$\frac{QM_{cr}}{QD_c} = \left(\frac{PDD_c}{PM_c} \cdot \frac{\delta_c^q}{1 - \sum_r \delta_{cr}^q} \right)^{\frac{1}{1+\rho_c^q}}$$ (22)

$$QQ_c = QD_c + \sum_r QM_{cr}$$ (23)

$$PQ_c \cdot (1 - tq_c) \cdot QQ_c = PDD_c \cdot QD_c + \sum_r PM_{cr} \cdot QM_{cr}$$ (24)

$$QT_c = \sum_{c' \in C'} icm_{cc'} \cdot QM_{c'} + ice_{cc'} \cdot QE_{c'} + icd_{cc'} \cdot QD_{c'}$$ (25)

$$\overline{CPI} = \sum_{c \in C} PQ_c \cdot cwts_c$$ (26)

$$DPI = \sum_{c \in C} PDS_c \cdot dwts_c$$ (27)

Institutional Incomes and Domestic Demand Equations

$$YF_f = \sum_{a \in A} WF_f \cdot \overline{WFDIST}_{fa} \cdot QF_{fa}$$ (28)

$$YIF_{if} = shif_{if} \cdot \left[YF_f - trnsfr_{row\,f} \cdot EXR \right]$$ (29)

$$YI_i = \sum_{f \in F} YIF_{if} + \sum_{i' \in INSDNG'} TRII_{ii'} + trnsfr_{i\,gov} \cdot \overline{CPI} + trnsfr_{i\,row} \cdot EXR$$ (30)

$$TRII_{ii'} = shii_{ii'} \cdot (1 - MPS_{i'}) \cdot (1 - \overline{tins}_{i'}) \cdot YI_{i'}$$ (31)

$$EH_h = \left(1 - \sum_{i \in INSDNG} shii_{ih} \right) \cdot (1 - MPS_h) \cdot (1 - \overline{tins}_h) \cdot YI_h$$ (32)

$$PQ_c \cdot QH_{ch} = PQ_c \cdot \gamma_{ch}^m + \beta_{ch}^m \cdot \left(EH_h - \sum_{c' \in C} PQ_{c'} \cdot \gamma_{c'h}^m \right)$$ (33)

$$QINV_c = IADJ \cdot \overline{qinv}_c$$ (34)

$$QG_c = \overline{GADJ} \cdot \overline{qg}_c$$ (35)

$EG = \sum_{c \in C} PQ_c \cdot QG_c + \sum_{i \in INSDNG} trnsfr_{i\ gov} \cdot \overline{CPI}$	(36)
System Constraints and Macroeconomic Closures	
$YG = \sum_{i \in INSDNG} \overline{tins}_i \cdot YI_i + \sum_{c \in CMNR} tm_c \cdot pwm_c \cdot QM_c \cdot EXR + \sum_{c \in C} tq_c \cdot PQ_c \cdot QQ_c$ $+ \sum_{f \in F} YF_{gov\ f} + trnsfr_{gov\ row} \cdot EXR$	(37)
$QQ_c = \sum_{a \in A} QINT_{c\ a} + \sum_{h \in H} QH_{c\ h} + QG_c + QINV_c + qdst_c + QT_c$	(38)
$\sum_{a \in A} QF_{f\ a} = QFS_f$	(39)
$YG = EG + GSAV$	(40)
$\sum_{r\ c \in CMNR} pwm_{cr} \cdot QM_{cr} + \sum_{f \in F} trnsfr_{row\ f} = \sum_{r\ c \in CENR} pwe_{cr} \cdot QE_{cr} + \sum_{i \in INSD} trnsfr_{i\ row} + FSAV$	(41)
$\sum_{i \in INSDNG} MPS_i \cdot \ 1 - \overline{tins}_i \ \cdot YI_i + GSAV + EXR \cdot FSAV = \sum_{c \in C} PQ_c \cdot QINV_c + \sum_{c \in C} PQ_c \cdot qdst_c$	(42)
$MPS_i = \overline{mps}_i \cdot \ 1 + MPSADJ$	(43)
Capital Accumulation and Allocation Equations	
$AWF_{f\ t}^{a} = \sum_{a} \left[\left(\frac{QF_{f\ a\ t}}{\sum_{a'} QF_{f\ a'\ t}} \right) \cdot WF_{f\ t} \cdot WFDIST_{f\ a\ t} \right]$	(44)
$\eta_{f\ a\ t}^{a} = \left(\frac{QF_{f\ a\ t}}{\sum_{a'} QF_{f\ a'\ t}} \right) \cdot \left(\beta^a \cdot \left(\frac{WF_{f,t} \cdot WFDIST_{f\ a\ t}}{AWF_{f\ t}^{a}} - 1 \right) + 1 \right)$	(45)
$\Delta K_{f\ a\ t}^{a} = \eta_{f\ a\ t}^{a} \cdot \left(\frac{\sum_{c} PQ_{c\ t} \cdot QINV_{c\ t}}{PK_{f\ t}} \right)$	(46)
$PK_{f\ t} = \sum_{c} PQ_{c\ t} \cdot \frac{QINV_{c\ t}}{\sum_{c'} QINV_{c'\ t}}$	(47)
$QF_{f\ a\ t+1} = QF_{f\ a\ t} \cdot \left(1 + \frac{\Delta K_{f\ a\ t}^{a}}{QF_{f\ a\ t}} - \upsilon_f \right)$	(48)
$QFS_{f\ t+1} = QFS_{f\ t} \cdot \left(1 + \frac{\sum_{a} \Delta K_{f\ a\ t}}{QFS_{f\ t}} - \upsilon_f \right)$	(49)