Has climate change promoted urbanization in Sub-Saharan Africa?

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Abstract

This paper documents a significant impact of variations in climatic conditions on urbanization in sub-Saharan Africa, especially in arid countries. By raising farm income, greater moisture availability retards the growth of nearby cities, while drier conditions accelerate it. This local impact is stronger than the effect on national primate cities. There is also evidence of a shift to non-farm activities during tough times, and women are more likely to drop out of the labor force. Finally, climatic conditions also affect city incomes in countries with high agricultural dependence, presumably through spending on urban goods and services by farmers benefiting from productivity increases. Overall, these findings confirm a strong link between climate and urbanization. Predicted negative impacts of climate change on agriculture will therefore likely accelerate the growth of African cities that have struggled to absorb a growing population into productive jobs.

JEL Codes: O10, O55, R12

Key words: Africa, Urbanization, Climate Change

Sector: Urban

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Has climate change promoted urbanization in Sub-Saharan Africa?

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1. Introduction

Sub-Saharan Africa (hereafter Africa) has been urbanizing over the last twenty years, with cities and towns growing at an annual rate of close to four percent. Its urban population of 335 million now exceeds the total population of the United States. Nevertheless, almost two-thirds of Africa's population still lives in rural areas. How urbanization evolves in Africa over the next decades will determine where people and jobs locate and where public services should be delivered. A longstanding debate in the global development literature about the relative importance of push versus pull factors in urbanization has focused recently on Africa. Recent papers have assessed the contribution of pull factors including structural transformation driven by human capital accumulation and trade shocks (e.g., Fay and Opal 2000; Henderson, Roberts and Storeygard 2013) and of resource rent windfalls spent in cities (Jedwab, 2011; Gollin, Jedwab and Vollrath 2013). Other papers examine push factors including civil wars (Fay and Opal 2000), poor rural infrastructure (Collier, Conway and Venables 2008), and our focus, climate variability and change (Barrios, Bertinelli and Strobl 2006; see also Munshi 2003 on Mexico-US migration and Barrios, Bertinelli and Strobl 2010 on the effects of climate on economic development).

This paper focuses on the consequences of climate variability and change for African urbanization and the transformation of the rural sector. We build on the existing literature for Africa by controlling for arbitrary national trends and by considering multiple urbanization-related outcomes. Over the last 40 years much of Africa has experienced a decline in moisture availability ("wetness" hereafter), a combination of precipitation and potential evaporation, which is itself a function of temperature. Figure 1 shows average wetness for the 1950s and 1960s. As Figure 2 shows, much of the strongest (10-50%) decline in wetness over the subsequent forty years occurred in parts of Africa that were already drier (wetness under 0.65 or between 0.65 and 0.95 in Figure 1), making the areas most vulnerable to variability more vulnerable. This decline in wetness has surely impacted agricultural productivity, and we show this has pushed people to the urban sector. However wetness declines may have other inter-related effects. We provide new evidence on two of these. First, lower productivity in agriculture may have negative effects on nearby towns, muting migration effects. Second, those living in the rural sector are not all in agriculture, and rainfall declines have affected occupational choices for those left in the rural sector.

Figure 1: Historical levels of wetness (precipitation / potential evapotranspiration)

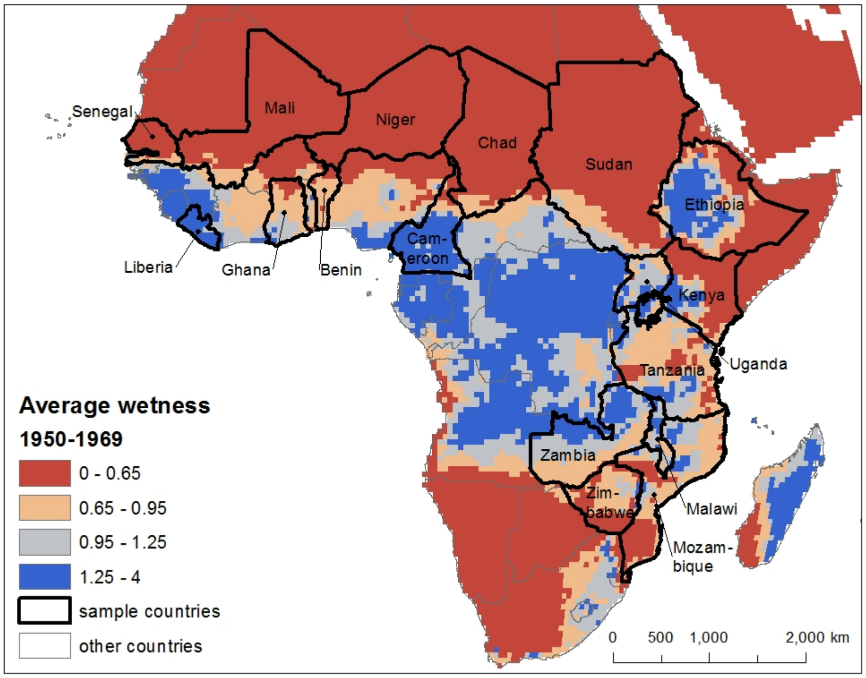
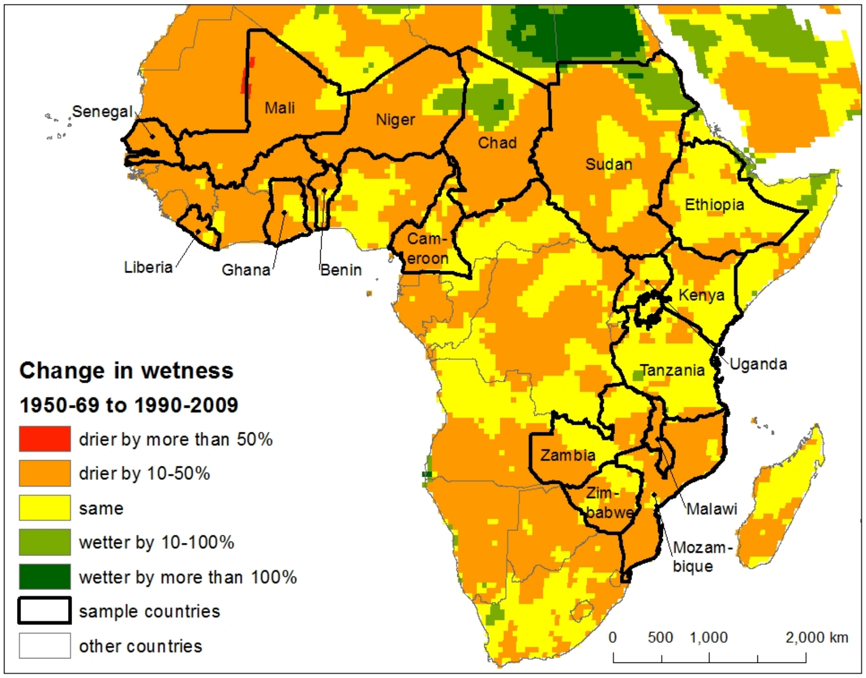


Figure 2: Drying out of Africa



While our analysis necessarily focuses on the impacts of past climate variability, the specter of future climate change is a strong motivation. There is a growing literature on climate change in Africa by climatologists and geologists who have a much longer term perspective. We will review this literature later. While future climate in Africa is clearly uncertain, further drying out is generally predicted for parts of Africa and assessing the consequences is critical to understanding Africa's development prospects.

The first question we ask is whether decreased wetness has contributed to the growth of nearby cities, perhaps by forcing farmers to abandon their land due to falling agricultural returns. For this question, we depart from the existing literature which either reports on local and often qualitative case studies or looks at the effect of climatic changes on urbanization at the aggregate national level (e.g., Barrios, Bertinelli and Strobl 2006), where much of the geographic heterogeneity is lost. Aggregate studies also use population data reported at regular 5 or 10 year intervals. These data rely heavily on interpolation, especially in Africa where many censuses are infrequent and irregularly timed. We construct a new data set of urban growth for sub-national regions based on actual census data, not interpolations. We look first at local, within-district urbanization. In more arid countries, a one standard deviation increase in the annualized growth rate of wetness lowers the annualized growth rate of urban shares in districts by about by 25-30% from the mean for urbanization growth rates. Moreover, across the range of annualized growth in wetness, moving from the lowest to highest wetness growth rate lowers the annualized growth in urban share by 160% from the mean, a huge effect. These results are robust to the inclusion of a variety of controls and hold overall for an unbalanced 50-year panel of 193 districts in 17 African countries (both arid and wetter). Beyond this baseline result on within district urbanization, we find that changes in wetness in the rest of the country also impact primate city growth. In arid countries in a panel framework, a one standard deviation increase in the growth of wetness in the rest of the country reduces the primate city annualized growth rate by a more modest 10%.

Our second question is how wetness changes occupational choice in the rural sector. This question is motivated by the little-noticed transformation over the last 20 years in many African rural sectors, where people are moving from farm to non-farm occupations. For example, data for Benin, Malawi, and Niger in the period 1987-1996 all showed between 85 and 91% of the rural male labor force working in agriculture. By the 2006 to 2008 round of surveys, 57-72% of the rural male labor force in these countries remained in agriculture.[1] Based on individual-level observations from the Demographic and

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[1] For Benin we are comparing the 1996 and 2006 DHS surveys. For Niger it is the 1992 and 2006 DHS, while for Malawi it is the 1987 and 2008 IPUMS. See details later in this paper.

Health Surveys (DHS), we show more systematically that declines in wetness increase the probability of moving from farm to non-farm rural occupations. For this sample in the long difference panel-type specification, a one standard deviation (levels) increase in wetness for women lowers the probability of working in agriculture by about 0.020 - 0.032. Over the full range of wetness, the change in probability is about 0.2. Estimates for men are in the same direction but somewhat smaller and noisier. Women are more likely to drop out of the rural work force altogether when climate conditions for farming are poor.

Finally, we examine how climate change affects the relationship between the local urban and rural sectors, building on Jedwab's (2011) historical study of Ghana and Cote d'Ivoire. We test whether better rural climate conditions raise incomes in local cities. We expect that better farming conditions increase productivity in rural hinterlands, which presumably leads to increased spending by farmers on urban goods and services. Using a measure of income derived from the intensity of nighttime urban lights, we find evidence supporting this link, but only in countries with a strong dependence on agriculture. For these countries, while poorer climate may lower the relative return to being in the local rural sector, it also negatively impacts local towns by lowering urban incomes. We expect this to mute the local rural to urban migration response to poorer climate, relative to a situation where the economic fortunes of local towns are less dependent on the rural sector.

Overall, our results suggest that if future climate change will have the negative impacts on agriculture that many climate scientists and agronomists expect for Africa, there may be even greater population pressure in African cities that already struggle to absorb a growing population. But we also expect a further transformation of the rural sector, as people move out of farming into non-farm rural production and services.

The following section reviews the literature on predicted impacts of climate change in Africa and on the link between climate and development outcomes including urbanization. Section 3 describes the construction of the core climate and urbanization indicators used in the base analysis. Other data sets used are described in the relevant empirical sections. Section 4 presents the base analysis of the impact of changes in moisture availability on local urbanization, followed by the analyses of migration to primate cities, responses within the rural sector, and local urban income growth in Section 5. Section 6 concludes.

2. Climate impacts on economic development and urbanization

The African climate has always been highly diverse and highly variable. It ranges from the hyperarid Sahara to the humid tropics of Central Africa. In places like the West African Sahel, long droughts have followed extended wet periods. Africa's climate is shaped by the intertropical convergence zone, seasonal monsoons in East and West Africa, and the multi-year El Nino/La Nina Southern Oscillation [ENSO] that cause changes in Pacific Ocean temperatures with an indirect effect on African weather (Conway 2009). These processes influence temperatures and precipitation across the continent including meteorological droughts, especially in the Sahel, the Horn of Africa and the Southern African drylands, as well as severe floods, most recently in Kenya in 2013. Climate records indicate a warming trend over Africa during the 20th Century, continuing at a slightly faster pace in the first decade of the 21st Century, independently of ENSO impacts (Collins 2011; Nicholson, Nash, Chase, et al. 2013).

Climate researchers predict future climate change using various emission scenarios as inputs to several different assessment models. The underlying scenarios range from aggressive mitigation of greenhouse gases to a continuation of current trends. While there is fairly broad consensus about global average temperature trends, regional scenarios of temperature and particularly of precipitation patterns remain quite uncertain. Researchers from the Potsdam Institute for Climate Impact Research recently reviewed the predictions of a number of credible climate models for regional climate change in Africa based on two global scenarios: a more optimistic 2°C scenario and in a 4°C scenario which, given current policies, is predicted to occur by the end of the century with a probability of 40 percent (see World Bank 2013). These projections suggest that with 2°C average global warming, rainfall in the Horn of Africa and the Sahel countries will increase. This could reduce the risk of drought but also bring more frequent flood events if, as predicted, rainfall events will be more concentrated (see also Vizy, Cook, Crétat and Neupane 2013). Precipitation and groundwater recharge in parts of Southern and coastal West Africa is projected to decrease by as much as 50-70 percent. Temperature is projected to increase by an average of 1.5°C in Africa with 2°C global warming, which could be reached as early as 2030. The area exposed to greater heat extremes is expected to expand by 5 percent by then, and by 45 percent by 2050. Under a global 4°C scenario these trends would be exacerbated. With falling precipitation and rising temperatures, the trend of a "drying out" with worsening agricultural growing conditions in large parts of Africa is likely to continue as larger areas will experience increased aridity, especially in coastal West African countries and in Southern Africa.

Extreme climate conditions on the continent mean that many African farming systems operate in fairly marginal conditions, even in the best of times. Agriculture worldwide will feel the effects of climate change more directly than any other sector. A number of studies have estimated the impact on the value of crop and livestock production under various scenarios, with a focus on the United States (Mendelsohn, Nordhaus and Shaw 1994, Schlenker, Hanemann and Fisher 2006, Deschênes and Greenstone 2007). Results from these studies include increasing aggregate U.S. crop values but also losses in most U.S. counties. Estimating these impacts for Africa is more difficult because geographically detailed agricultural output information is rarely available. Nevertheless, a significant economic literature on climate change and African agriculture has emerged. Some studies find modest or even positive impacts under optimistic scenarios of limited climate change and successful adaptation (Kurukulasuriya, Mendelsohn, Hassan, et al. 2006, Kurukulasuriya and Mendelsohn 2008; Calzadilla, Zhu, Rehdanz, Tol and RIngler 2013). The majority of studies, however, predicts yield losses for important staple and traded crops of 8 to 15 percent by mid-century, with much higher losses of more than 20 percent and up to 47 percent by 2090 for individual crops (especially wheat) and under pessimistic climate scenarios (Kurukulasuriya, Mendelsohn, Hassan, et al. 2006, Kurukulasuriya and Mendelsohn 2008; Lobell, Burke, Tebaldi, et al. 2008; Schlenker and Lobell 2010; Thornton, Jones, Ericksen and Challinor 2011; Calzadilla, Zhu, Rehdanz, Tol and RIngler 2013; and the meta-analyses by Piguet 2010; Roudier, Sultan, Quirion and Berg 2011; Knox, Hess, Daccache and Wheeler 2012). Given agriculture's importance in African economies—it accounted for 12 percent of GDP in 2011 in the region and more than half of employment—such impacts would significantly threaten the continent's development prospects. Even today, unfavorable rainfall trends may have contributed to Africa's poor growth performance over the last 40 years, explaining between 15 and 40 percent of today's gap in African GDP relative to other developing countries (Barrios, Bertinelli and Strobl 2010).

Largely through its impact on agriculture, an emerging literature is finding broader impacts of variations in temperature and rainfall on human capital and political outcomes. The impact of climate-related natural disasters has received much attention (e.g., Alderman, Hoddinot and Kinsey 2006). Some recent papers suggest that less dramatic variations in climatic conditions experienced after, or even before, birth can also have long term consequences. Deschênes, Greenstone and Guryan (2009) find that exposure to extreme hot temperatures during pregnancy increased the probability of low birthweight in a large data set covering the United States. Favorable conditions during early life among rural inhabitants in Indonesia lead to improved outcomes in terms of health, schooling and socioeconomic status (Maccini and Yang 2009). Women who experienced 20 percent higher than normal rainfall during their first year of life are almost 5 percent less likely to self-report poor or very poor health. A study in India, in contrast, finds that favorable climatic conditions can have negative impacts on schooling in later childhood (Shah and Steinberg 2013). Investments in human capital were found to be counter-cyclical, higher in drought years when the opportunity costs of schooling versus agricultural work were lower. Several studies also find that adverse climatic conditions increase the risk of conflict in Africa (Burke, Dykema, Lobell, Miguel and Satyanath 2009; Hsiang, Meng and Cane 2011; O'Loughlin, Witmer, Linke, et al. 2012). They find that higher temperatures increase and wetter conditions decrease the probability of violent conflict or civil war. Macro-level analysis by Brückner and Ciccone (2011), on the other hand, suggests that negative income shocks related to rainfall variations provide opportunities for improvements in democratic institutions. A negative transitory income shock of 1 percent caused by rain shortages improves democracy scores by 0.9 percentage points and the probability of a democratic transition increases by 1.3 percentage points.

The first question in this paper is whether climatic conditions have significant effects on the speed of urbanization in districts in African countries. This question needs to be set within the overall context of urbanization in Africa, where studies are hampered by the generally low quality of census data and the scarcity of detailed migration surveys. There is consensus that migration and urbanization are shaped by complex processes. There is not just rural-to-urban migration but also moves between rural areas, between cities and even from cities back to rural areas, with some of these moves being temporary or circular migration (Parnell and Walawege 2011). Urban growth is also driven by persistently high fertility rates in cities and by the re-classification of peri-urban areas. McGranahan, Mitlin, Satterthwaite, Tacoli, and Turok (2009) calculate that migration only contributes one-third of total urban growth in Africa. Furthermore, while the African urban system used to be dominated by a few very large cities, a large number of smaller and medium sized cities have more recently emerged as nearby destinations of rural migrants. Detailed empirical case studies confirm the importance of short distance migration (see also the review by Jonsson 2010). In Burkina Faso, for instance, looking at recalled first migration episodes of people in the rural sector, Henry, Schoumaker, and Beauchemin (2004) find people are more likely to migrate to other rural areas, cities and abroad in areas with rainfall declines. Such migration dynamics could be self-propelling. In a detailed study of Mexican migrants to the U.S., Munshi (2003) finds that past rainfall deficits in origin communities increase migrant's job prospects at the destination by having created larger job networks of previous migrants from those communities.

Finally, several recent macro-level studies have also investigated the role of climate factors on African migration. Marchiori, Maystadt, and Schumacher (2013) divide drivers of migration into those related to (dis-)amenities (potential spread of disease; risk of floods or heat waves) and economic geography (most importantly, agricultural performance determining migration decisions). They find both channels to be important with temperature and rainfall anomalies estimated to have triggered 5 million migration movements between 1960 and 2000. In similar country level panel analysis, Naudé (2010) finds little evidence of a direct influence of environmental factors, while Barrios, Bertinelli and Strobl (2006) estimate an increase in the urban share of 0.45 percent with a reduction in rainfall of 1 percent. There has been much less consideration of year-to-year climatic variability in such models, despite evidence that the length of growing period, for instance, varies considerably in much of Africa (Vrieling, de Beurs and Brown 2011; Vrieling, de Leeuw and Said 2013). An exception is Marchiori, Maystadt and Schumacher (2013) who suggest that environmentally induced income levels—proxied by per capita GDP—may be more important for migration decisions than variability.

What emerges from this literature is accumulating evidence that climate change influences agricultural, human capital and other socioeconomic outcomes in Africa and elsewhere. While there is still incomplete knowledge about the pace and precise impacts of future climate change, it is likely that continued warming and resulting precipitation changes will influence economic development, and urbanization, in the future. For Africa, the challenges may be greater because adaptation in the agricultural sector appears to be more difficult. The potential for offsetting influences on productivity in agriculture in Africa may be less because technological change in Africa's agricultural rural sector has been much slower than in other regions. Fertilizer use, for instance, has stagnated in Africa at low levels since 1980, while it has risen tenfold in Asia and Latin America (Cooper, Stern, Noguer and Gathenya 2013), and only 4 percent of agricultural land is irrigated compared to 18 percent globally (You, Ringler, Nelson, et al. 2010). The combination of an already difficult climate, significant projected climate change and limited adaptation capacity has led some observers to state that Africa will be more affected than other regions (e.g., Collier, Conway and Venables 2008). In an optimistic scenario, climate change will provide the incentives to invest in Africa's rural sector, strengthening its resilience. A different and perhaps more pessimistic scenario could mean that climate change further accelerates rural-to-urban migration towards cities that are poorly equipped to integrate new residents and in countries not ready for structural transformation from agriculture to manufacturing (Michaels, Rauch, and Redding, 2012).

The question whether changes in climate accelerate urbanization processes is thus of key importance to Africa.

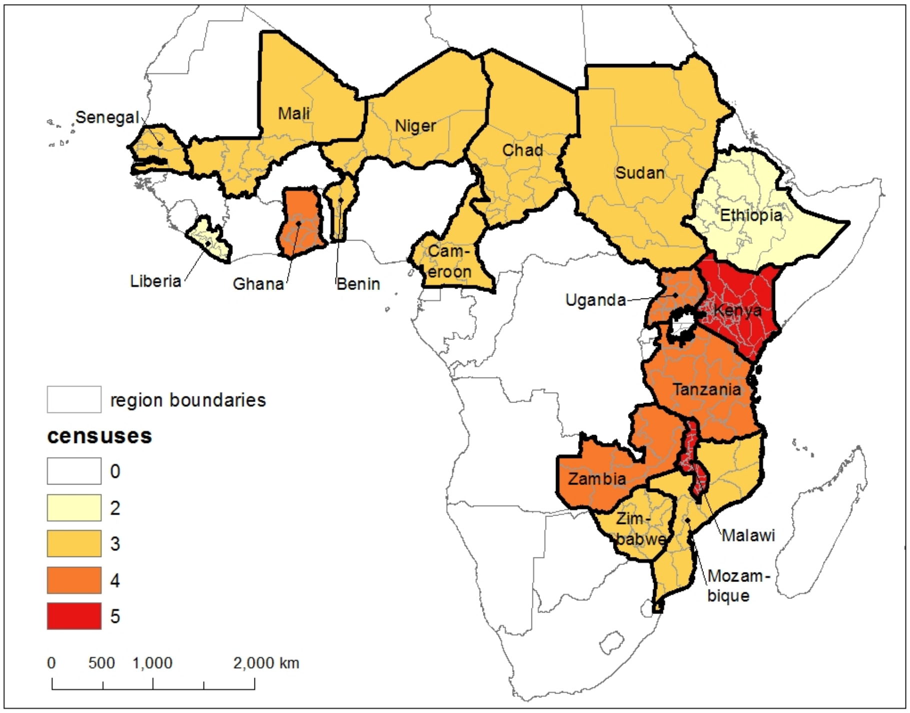
3. Data on urbanization and climate

Scarcity of demographic and economic data hampers empirical research climate effects in Africa. Registration systems are virtually non-existent, many countries carry out censuses only irregularly, and sample surveys such as the DHS are infrequent and provide little information before 1990. While there are now a number of geographically detailed data sets on climatic indicators that are increasingly used by economists (see Auffhammer, Hsiang, Schlenker, and Sobel 2013), most studies have employed national level population and economic data sets which are readily available from the UN and other agencies and which for African countries rely heavily on imputations and interpolations.

For this paper we use urbanization and population measures for sub-national regions (provinces and districts) directly from census reports. We include countries that had at least two available censuses with information on urban and rural population for a complete or nearly complete set of sub-national units where district boundaries either changed little or common units over time can be defined. We prioritized countries with the most censuses, the largest populations and the largest land areas—ideally encompassing multiple climate zones and capturing the more affected drier regions in West (Sahel), East and Southern Africa. The data on rural and urban population totals were extracted mostly from hardcopy census publications obtained from libraries such as the U.S. Library of Congress. The final sample contains 15 countries with three or more censuses and two countries with two censuses between 1960 and 2010 (Figure 3). The most notable omission is Nigeria, Africa's most populous country, because of concerns over the quality of census figures (see, e.g., Okafor, Adeleke and Oparac 2007). Each of the 17 countries in the sample is divided into a number of provinces or districts yielding observations for 193 units (which we refer to as districts in this paper). The average rural and urban populations per district across all countries and census years are 850,120 and 264,547, respectively. Annex 1 lists countries and census years included in the analysis.

In the empirical analysis we use both the complete panel of intercensal periods and a long-difference data set capturing longer-term, inter-generational changes. We restrict the panel to consecutive censuses no more than 18 years apart. This removes Liberia, for which the period between the only two usable censuses is 34 years. For the long-difference estimates we only include census pairs at least 17 years apart. This excludes Ethiopia, for which we only have censuses for 1994 and 2007. Thus, our estimation sample consistently includes 16 countries, but the country composition changes slightly.

Figure 3: Countries included in the analysis by number of censuses



With few exceptions, most studies of climate impacts focus exclusively on precipitation. But what is important for agriculture is not only the amount of rainfall, but how much moisture is actually available for plant growth. Thus, a better measure of climatic agricultural potential is therefore precipitation divided by potential evapotranspiration, which is a non-linear function of temperature, increasing in the relevant range. Although this measure is often called an aridity index and used to define aridity zones (UNEP 1992), we call it a wetness or moisture availability index, because larger values indicate relatively greater water availability, with values above one indicating more moisture than would be evaporated given prevailing temperature. Precipitation and temperature data are from the University of Delaware gridded climate data set (Matsurra and Willmott 2009). We estimated monthly potential evapotranspiration (PET) from 1950 to 2010 using the Thornthwaite method based on temperature, number of days per month and average monthly day length, and subsequently summed monthly values to obtain annual totals (see, e.g., Willmott, Rowe and Mintz 1985 for details). More specifically, potential evapotranspiration (PET) for month *i* is calculated as:[2]

$$PET_i = \left(\frac{N_i}{30}\right)\left(\frac{L}{12}\right)\begin{cases} 0, \ T_i < 0°\mathrm{C} \\ 16(10T_i/I)^{\alpha}, \ 0 \leq T_i < 26.5 \\ -415.85 + 32.24T_i - 0.43{T_i}^2, \ T_i \geq 26.5 \end{cases},$$

where T_i is the average monthly temperature in degrees Celsius, N_i is the number of days in the month, L_i is day length at the middle of the month, $\alpha = (6.75 \times 10^{-7})I^3 - (7.71 \times 10^{-5})I^2 + (1.792 \times 10^{-2})I + 0.49$, and the heat index $I = \sum_{i=1}^{12}\left(\frac{T_i}{5}\right)^{1.514}$ where T_i indicates the 12 monthly mean temperatures.

Figure 4 shows average annual country-level wetness trends for the countries in our sample, indicating the long term downward trend over the last 60 years, consistent with Figure 2. It also shows the high inter-annual variability of wetness in these countries. The climate data sets have a spatial resolution of 0.5 degrees, which corresponds to about 55 km at the equator. To generate district level climate indicators, we averaged grid cell values that overlapped with the corresponding sub-national unit, proportionally to area[3] in the case of cells that cross district boundaries.

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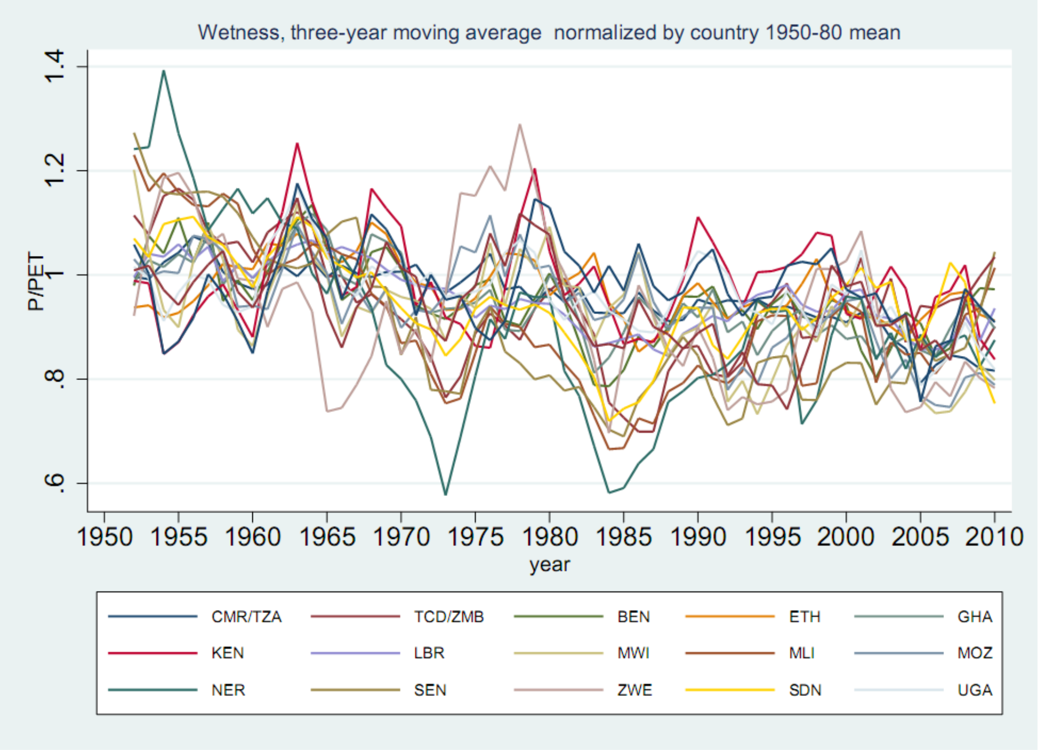
[2] The Penman method provides a more precise estimate of PET, but requires data on atmospheric and climate conditions that are not available consistently for the area and time period of this study.

[3] In practice, numberof 0.1-degree sub-cells.

Figure 4: Trend in the wetness indicator (precipitation / potential evapotranspiration) in sample countries



4. The impact of climate variability on local urbanization

Our first research question is whether changes in agroecological endowment as measured by the wetness index influence urbanization rates. Our focus is on local migration processes—from rural areas to provincial or district centers—that are not captured by national level analysis. Annex 2 presents the traditional two-sector model that underlies our estimation strategy (see also Henderson, Roberts and Storeygard 2013). The basic premise is that people migrate between the urban and rural sector to equalize incomes. In this context rural is synonymous with agriculture, so urbanization will rise when returns to agricultural activities fall. From the literature we reviewed earlier we know adverse weather conditions lower returns to agriculture. Conversely, favorable agro-ecological conditions will slow down urbanization or even cause reverse migration.

The simple two-sector model does not consider two alternative responses from shocks to the agricultural sector. One is that while higher farm incomes should, on balance, restrain urbanization, the effect may be muted by rural-urban synergies. Additional farm income could be invested in labor saving technology and at least some of the surplus will be spent or invested in cities (see Gollin, Jedwab and

Vollrath 2013 for a discussion of such "consumer cities"). Second, besides rural-to-urban migration, rural residents may shift within the rural sector from farm to non-farm activities. As noted earlier, data from the Demographic and Health Surveys (DHS; see www.measuredhs.com) and the Integrated Public Use Microdata Series (IPUMS; Minnesota Population Center) show the share of agricultural employment in rural areas falling, sometimes substantially, between the 1990s and 2000s, indicating the importance of the rural non-farm sector in some countries in Africa.

A number of additional factors could affect our analysis. Although moisture availability is arguably the most important determinant of annually variable agricultural potential, it may interact with soil quality, especially the soil's ability to retain water. In some formulations we interact changes in aridity with soil water retention and soil pH data from Ramankutty, Foley, Norman and McSweeney (2002). Acidic soils (with a low pH) and those with very high pH tend to be less fertile. Although soil degradation can change soil conditions over the time scale of decades (see UNEP 1992), data on these dynamics are not consistently available, so soil quality is time invariant in our analysis. We also include interactions with irrigation infrastructure (Siebert et al 2007), which can help cope with rainfall deficits, but as mentioned earlier, only 4 percent of African farmland is irrigated. Besides the overall change in wetness between census years, the variability of conditions within and between years could also affect farmers' decisions to migrate. Relatively steady declines could lead to a buildup of sentiment to migrate, or it could be high variability that encourages exit from the rural sector because of larger uncertainty. We therefore experiment with a measure of rainfall variability in selected specifications. Finally, we may see less of a migration response to changes in climate in areas that are already fairly urbanized, so we allow changes in urbanization rates to depend on the initial urbanization level.

4.1 Base specifications and results

Our base specification is

$$u_{ijt} = \alpha_{jt} + \beta w_{ijt,smooth-lag} + \varepsilon_{ijt} \qquad (1)$$

where variables for district i, in country j, in year t, are defined as follows:

u_{ijt} is annualized growth of the urban population share from t to $t - L_{jt}$;
α_{jt} is a country-year fixed effect controlling for changes in country conditions;
$w_{ijt,smooth-lag} = \left[lnW_{ij,t-4,smooth3} - lnW_{ij,t-L_J-4,smooth3}\right]/L_{jt}$;
$W_{ij,t-4,smooth3}$ is average wetness from $t-4$ to $t-6$; and
L_{jt} is number of years between census in year t and the prior census.

Growth in urbanization is just a function of growth in wetness. This is derived from our theory, as exemplified by equation (4). In a more extended specification, we condition growth in urbanization and wetness effects on the initial level of urbanization, where both effects may be dampened by high levels of urbanization:

$$u_{ijt} = \alpha_{jt} + \beta_0 w_{ijt,smooth-lag} + \beta_0 UN_{ij,first} + vUN_{ij,first}\, w_{ijt,smooth-lag} + \varepsilon_{ijt} \qquad (2)$$

where $U_{ij,first}$ is share urban in the district in the base period.

We consider both urbanization and wetness in terms of annualized intercensal growth rates in a quasi-first difference specification, rather than including district fixed effects, because each of our 16 countries has a different intercensal periods vary across countries.

This removes the effect of time-invariant district characteristics (distance to markets, soil quality and the like) on urbanization *levels*. Of course some of these factors may also affect urban share growth rates, an issue we pursue below. We control for country-year fixed effects to account for national time-varying conditions driving urbanization overall in a country. This also controls to some extent for variation between countries in the definition of urban areas, which poses a significant problem in cross-country urban analysis. What we are doing is demanding on the data—identification of climate effects must come from within country differences across districts in annualized growth rates of wetness.

Rather than assuming that the climatic conditions in the current period influence intermediate and long run migration, we experiment with lagging climate conditions by several years to allow for time to respond. As we will show below, working with a lag of 4 years fits the data well. To account for the large inter-annual variability of climate we also use a 3-year average smoothing of wetness index values. So, for example, the annualized rate of change in urban share between the 1965 and 1980 censuses is a function of the annualized rate of change in wetness between the average for 1959, 1960 and 1961 and the average for 1974, 1975 and 1976. Although this final choice is somewhat arbitrary, our results seem robust to various alternative definitions around these values. The basic panel estimation uses all 496 intercensal periods.

Besides a panel formulation we look at a long difference one. The long difference may capture “inter-generational” aspects of response to climate change. Intuitively, the beginning period represents the family’s recollection of climate experienced by the older generation and the last period the climate experienced by the younger generation, with the annualized difference being the growth rate between generations. The long difference is specified so as to be less subject to the noise created by annual climate variability still remaining in the panel with 3 year smoothing. The long difference specification includes only those observations for which the intercensal period is at least 17 years for a total of 186 observations. Given that, we can now smooth over 8 years, with the first year of the 8 being 4 years prior to the current, as for the panel. Long difference results are very robust to changes in the degree of smoothing and length of lagging.

Finally, we expect only limited response to moderate changes in climate in the more humid parts of Africa. We therefore run each regression for the entire data set as well as for only the districts in countries located in arid regions, where the upper threshold is set at an average precipitation over potential evaporation ratio of 0.95 between 1950 and 1969—i.e., all countries that, on average, experienced a moisture deficit during that period.

In Table 1 we present means, medians, standard deviations, and ranges for the estimating variables, to use in interpreting magnitudes of coefficients in the regressions and different samples to follow. We note that the annualized growth rate of wetness in all samples is negative, consistent with Figure 2 and that the growth rate in the share urban is positive, reflecting a basic underlying trend.

Table 1: Summary statistics, panel and long difference

	Panel								Long difference			
	All countries				Arid countries				All countries		Arid countries	
	Mean (s.d.)	Median	Range	N	Mean (s.d.)	Median	Range	N	Mean (s.d.)	N	Mean (s.d.)	N
Annualized growth in percent urban	0.0308 (0.0484)	0.0200	0.4637	496	0.0243 (0.0408)	0.0171	0.4637	203	0.0270 (0.0322)	186	0.0224 (0.0337)	94
Annualized growth in wetness	-0.0051 (0.0167)	-0.0048	0.1093	496	-0.0021 (0.0156)	-0.0007	0.1055	203	-0.0031 (0.0078)	186	-0.0033 (0.0105)	94
Annualized growth in rainfall	-0.0031 (0.0164)	-0.0031	0.1083	496	-0.0003 (0.0154)	0.0008	0.1047	203	-0.0022 (0.0076)	186	-0.0019 (0.0103)	94
Annualized growth in temperature	0.0013 (0.0017)	0.0010	0.0099	496	0.0010 (0.0013)	0.0009	0.0075	203	0.0005 (0.0007)	186	0.0008 (0.0007)	94
Base share urban	0.1419 (0.2109)	0.0628	1	496	0.1887 (0.2192)	0.1150	0.9882	203	0.1553 (0.2108)	186	0.1884 (0.2133)	94
Gini, within year monthly accumulation of rain	0.4951 (0.1355)	0.5193	0.5528	496	0.5482 (0.1208)	0.5476	0.5387	203	0.5033 (0.1401)	186	0.5707 (0.1154)	94
Dummy: No irrigation structures in data	0.2984			496	0.1379			203	0.2849	186	0.1489	94
Standard deviation of wetness level over growth interval	0.1379 (0.0915)	0.1388	0.4567	496	0.0745 (0.0668)	0.0539	0.3047	203	0.1414 (0.0724)	186	0.0975 (0.0543)	94
Soil water retention index	121.3300 (-23.99)	126.4586	112.2768	496	114.5459 (21.6331)	117.4686	112.2259	203	119.1035 (23.4931)	186	113.7570 (22.2664)	94
Soil ph	0.7616 (0.1999)	0.7999	0.7252	493	0.8204 (0.1641)	0.8351	0.6765	200	0.7566 (0.2153)	185	0.8421 (0.1550)	93
Average district total nonprimate population in base period	7.22m (5.6m)	5.23m	30.5m	35	7.31m (6.4m)	5.26m	30.5m	21				
Annualized population growth rate of primate city	0.0454 (0.0160)	0.0430	0.0769	35	0.0450 (0.0158)	0.0430	0.0717	21				

Note: soil ph data is missing for Zanzibar, Tanzania (afruid: 834026).

Table 2 presents results for the basic panel estimations and Table 3 for the long difference estimations. With changes in climatic conditions exogenous and randomized by nature across districts, identification of reduced form (or net) effects is straightforward. Overall, the results show that urbanization proceeds at a faster pace in areas that are getting drier (negative growth in wetness), with results for arid countries and for the long difference specifications being stronger. Changes in wetness will matter much less in countries with persistent rainfall surpluses and the consequences of climatic changes appear to play out over longer time periods.

More specifically in Table 2 for the panel, columns 1-3 show the results for all countries pooled together. While growth in wetness deters urbanization in the simple specification in column (1), the coefficient is insignificant. It is only in column (3) where we condition effects of wetness on initial urbanization that effects become statistically stronger. There, higher growth rates of wetness deter urbanization, but the effects of wetness diminish in areas that are more urbanized. The effects of climate on the growth rate of the share urban in areas already more urbanized may attenuate as the local economy becomes more urban oriented and the rural sector itself may become less dependent on farming.

In Table 2 in columns 4-8 we show the results for arid countries only. There, wetness effects in column 4 for the simplest specification are significant and the interactive effects with urbanization in column 6 are strong. In column 4, a one standard deviation increase in the growth rate of wetness (0.0156) leads to a reduction of 0.0078 in growth in the urban share from a mean of 0.0243, an over 30% reduction relative to the mean. In column 6, wetness effects at low levels of urbanization are double what they are in the base case, but effects die out by the time a district is just over 30% urbanized in the base period. We note that mean initial urbanization for the arid sample is a low 18.9%.

In Table 2 in columns 7 and 8, we replace our wetness index (P/PET) with rainfall and temperature. While temperature has little effect, precipitation shows similar effects as our moisture availability index, but results are generally statistically weaker. This indicates that it is the interaction between temperature and precipitation which is important and that accounting for non-linear effects of temperature and changing day length in the calculation of PET serves our econometric specification well.

The results in Table 2 are for the growth rate of wetness between inter-censal periods, where for these periods the level climate variables are smoothed over 3 years and lagged 4 years. Results not reported in this paper show that the findings are similar for smoothing of 2-4 years and for lags of 3 to 5 periods.

However, results are weak when there is no lag. While coefficients remain fairly large with no or little lag, they are not statistically significant. Specifically, with no lag, the coefficient (s.e.) on the growth rate in wetness is -0.58 (0.36), while that on the interaction with initial level of urbanization is 0.63 (0.82).

In Table 3 we conduct similar tests for the long difference dataset. Now the “inter-generational” results on wetness for all countries and for arid ones are quite similar, including a weaker interactive effect with initial urbanization. In both arid and all countries, in the simplest specifications in column 1, 2, 4, and 5, the coefficient on wetness is about -0.525. For a one standard deviation increase in the growth rate of wetness for arid countries (0.0105), the growth in urban share declines by about 0.0055 from a long difference mean of 0.0224, a 25% drop.

Table 2: Base results, Panel, all countries and arid countries only

	All countries			**Arid countries** (country average wetness from 1950 - 1969 < 0.95)				
	Smooth 3, lag 4			Smooth 3, lag 4				
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Growth in wetness	-0.217	-0.281	-0.527*	-0.567**	-0.499*	-1.034**		
	(0.23)	(0.22)	(0.269)	(0.28)	(0.265)	(0.445		
Base share urban		-0.069***	-0.057***		-0.054***	-0.045***	-0.054***	-0.050***
		(0.0082)	(0.0066)		(0.0115)	(0.00769)	(0.0115)	(0.0112)
Growth in wetness * base share urban			1.387**			3.104**		
			(0.638)			(1.504)		
Growth in rainfall							-0.405*	-1.005**
							(0.233)	(0.39)
Growth in temperature							4.713	3.835
							(3.355)	(3.987)
Growth in rainfall * base share urban								3.244***
								(1.226)
Growth in temperature * Base share urban								-0.908
								(12.22)
Country-year fixed effects	Yes	yes	yes	yes	yes	yes	yes	yes
N [Districts]	496	496	496	203	203	203	203	203
R-squared	0.266	0.341	0.353	0.344	0.418	0.481	0.422	0.485

Robust standard errors clustered at district level

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

Table 3: Long difference results, all countries and arid countries only

	All countries			**Arid countries** (country average wetness from 1950 - 1969 < 0.95)		
	Smooth 8, lag 4			Smooth 8, lag 4		
Growth in wetness	-0.550**	-0.506**	-0.887**	-0.510*	-0.533**	-1.115**
	(-0.234)	(-0.173)	(-0.386)	(0.273)	(0.231)	(0.485)
Base share urban		-0.0643***	-0.0562***		-0.0564***	-0.0380**
		(0.0107)	(0.0118)		(0.0167)	(0.0126)
Growth in wetness * base share urban			1.657			2.523
			(1.369)			(1.62)
Country fixed effects	yes	yes	yes	yes	yes	yes
N [districts]	186	186	186	94	94	94
R-squared	0.305	0.458	0.466	0.377	0.494	0.516

Robust standard errors clustered at country level

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

In Table 3 columns 3 and 6, adding the interactive effects of growth rate in wetness and initial share urban, as for the panel, raises the basic wetness coefficient in absolute value and has a large positive interactive effect, again indicating that wetness effects are stronger in less urbanized contexts. However the interactive effect is not significant.

In results not shown in Table 3, the long difference results are not very sensitive to either the number of years used in smoothing or in the lag chosen. Our choice of 8 and 4 respectively is somewhat arbitrary but does tend to lower standard errors on the wetness variable. The long term changes in climate across the different districts are less noisy than in the panel. For example in column 6, the coefficients (s.e.) on wetness and its interaction are respectively -1.12 (0.49) and 2.52 (1.62) while with 15 year smoothing and no lag, they are -1.24 (0.67) and 2.16 (1.75) respectively.

4.2 More complex specifications

Table 4 shows results controlling for four factors that may influence the relationship between urbanization and climate through base and interactive effects with the wetness growth rate measure. Most of the factors we consider are time-invariant and we find stronger effects for the long-difference without the potentially noisier within-panel variation. We also find statistically stronger effects for the larger sample of all countries rather than just arid ones for the long difference.[4] We focus our discussion on these results in columns 5 and 6. Column 5 enters these additional factors with no interactions, while column 6 interacts all factors with the wetness growth rate variable. Results without interactions are generally similar across samples and specifications (columns 1, 3, 5, and 7). However a major caveat for our discussion is that interactive effects for the long difference in columns 6 and 8 are quite different than for the panel (columns 2 and 4) where there are no effects. Overall, while the long difference results suggest certain interactive effects, it is difficult to draw definite conclusions.

In columns 5 and 6 for the long difference, our base results on wetness are similar to those in Table 3, noting that in column 6 the base coefficient on the wetness variable is now influenced by having so many interactive terms. We note four general results based on the four added factors from columns 5 and 6. First, in districts where there is no irrigation potential (i.e., irrigation has never been used) we would expect increased wetness to have less of an effect in slowing urbanization. This is indicated in the long difference specification where the interaction term in column 6 (and also 8) is significant at the 10 percent level. The negative coefficient for the irrigation dummy variable on its own likely captures conditions in less developed areas which result in less urbanization.

Second, a priori it is not clear whether large year-to-year variability in climatic conditions, as measured by the standard deviation of the annual wetness level during the inter-censal period, would promote or restrain urbanization. Our original concern was that a higher standard deviation would provide a noisier signal about long term changes and the degree of their persistence, dampening the effects on migration of long term wetness growth. It could also be that places with high natural variability are more adapted to difficult farming conditions and less influenced by an underlying trend. However, larger annual variability increases year-to-year risk and that could accentuate wetness effects on migration. In column

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[4] Identifying 13 coefficients beyond the fixed effects with 185 observations may be more plausible than with 93 observations, although both push the data.

Table 4: Controlling for other factors, panel and long difference data sets

	Panel				**Long Difference**			
	All countries (smooth 3, lag 4)		**Arid countries** (smooth 3, lag 4)		**All countries** (smooth 8, lag 4)		**Arid countries** (smooth 8, lag 4)	
Growth in wetness	-0.356*	-0.184	-0.544*	-0.602	-0.601***	-6.257***	-0.404	-1.854
	(-0.215)	(1.761)	(-0.276)	(2.720)	(-0.203)	(1.438)	(-0.250)	(4.408)
Base share urban	-0.0657***	-0.0551***	-0.0510***	-0.0440***	-0.0581***	-0.0552***	-0.0459**	-0.0463*
	(-0.00864)	(0.00706)	(-0.0122)	(0.00840)	(-0.0102)	(0.00915)	(-0.0175)	(0.0211)
Gini, within year monthly of accumulation of rain	-0.011	-0.0118	0.0125	0.0236	-0.00824	0.0297	-0.0119	0.0271
	(-0.0262)	(0.0258)	(-0.0259)	(0.0273)	(-0.0162)	(0.0247)	(-0.0297)	(0.0372)
Dummy: No irrigation structures in district	-0.00980**	-0.00733*	-0.00626	-0.00219	-0.0113***	-0.00987**	-0.0120*	-0.0128
	(-0.00399)	(0.00418)	(-0.00676)	(0.00707)	(-0.0038)	(0.00415)	(-0.00635)	(0.00905)
Std. dev. of wetness level over growth interval	0.0518*	0.0289	-0.0178	-0.00530	-0.0145	0.0725*	-0.165*	-0.0338
	(-0.0309)	(0.0323)	(-0.031)	(0.0321)	(-0.0278)	(0.0390)	(-0.076)	(0.100)
Soil water retention index	-0.000115	-0.000108	0.0000552	9.23e-05	-0.000145	-0.000201	0.000115	-1.22e-05
	(-0.000075)	(7.33e-05)	(-0.000098)	(9.54e-05)	(-0.00012)	(0.00013)	(-0.000099)	(0.00014)
Soil pH	-0.0255**	-0.0239*	0.000494	0.00417	-0.0328*	-0.0477**	-0.0226	-0.0507
	(-0.0128)	(0.0134)	(-0.0195)	(0.0152)	(-0.0173)	(0.0218)	(-0.0178)	(0.0422)
Base share urban * Growth in wetness		1.278*		3.045*		0.843		1.132
		(0.671)		(1.642)		(1.366)		(2.075)
Gini * Growth in wetness		-1.106		-0.651		10.26***		8.334*
		(1.435)		(1.718)		(3.186)		(4.734)
Dummy: No irrigation * Growth in wetness		0.345		0.114		0.675*		0.764*
		(0.293)		(0.552)		(0.393)		(0.431)
Std. dev. of wetness level * Growth in wetness		-2.997		-1.279		17.72**		4.162
		(2.351)		(2.677)		(7.191)		(9.846)
Soil water retention index * Growth in wetness		5.60e-05		-0.00159		0.00612		0.00688
		(0.00674)		(0.00951)		(0.0183)		(0.0212)
Soil pH * Growth in wetness		0.531		0.198		-3.374		-5.733
		(1.102)		(2.499)		(2.627)		(5.464)
Controls	Country-year fixed effects				Country fixed effects			
N [districts]	493	493	200	200	185	185	93	93
R-squared	0.362	0.380	0.432	0.493	0.493	0.523	0.523	0.567

Robust standard errors clustered at district level for panel, and at country level for long difference.
*** p<0.01, ** p<0.05, * p<0.1

6, consistent with our initial concern, we do find that in places of higher variability, the effect of growth in wetness on urbanization is dampened. But this effect is only significant in column 6.

Third, places with better soil conditions, which we measure with indicators of soil water retention capacity and soil pH, would reinforce the effect of wetness since both are favorable for agricultural production. However we find no interactive effects with soil. On the effects of soil alone, some columns weakly suggest that places with higher pH (less acidic) soils do indeed have lower urban share growth. Nevertheless, overall, there is little evidence that soils affect the growth rate in urban share directly or indirectly; but note that one would expect that soil quality affects the *level* of urbanization which is not represented in the differenced specification.

Fourth, there could be an effect of the distribution of wetness during the year. If the same annual rainfall is more concentrated in a few months of the year as is typical for monsoonal climates, it may allow for a more productive growing season relative to more uniform rainfall patterns. To measure the degree of "inequality" in rainfall across the year, we use a Gini measure, where the Lorenz curve is the accumulation of annual rainfall across months of the year ranked from lowest to highest rainfall and the Gini, as usual, is the degree of deviation from the 45 degree line of equal rainfall in every month. In column 6, a higher Gini and thus more inequality in rainfall across months of the year does indeed dampen the effects of the growth rate of wetness.

Finally, we looked at other factors such as national ethnolinguistic diversity which might limit migration responses across space and at growth in neighbors' wetness that could have competition effects. These showed no impacts. We also considered road accessibility measures but we only have these for later periods and they are obviously highly endogenous.

5. The effect of climate on other outcomes, relevant to the nature and pattern of urbanization

We explore three alternative ways that climatic conditions directly or indirectly affect urbanization. First, our specification to date examines the effect of climate on *relative* shifts within a district between the urban and rural sectors. But there can also be movements out of the district in response to climate changes and one key destination in developing countries is the primate city. In Africa where most counties have small populations, primate cities can dominate the urban landscape, although as noted earlier that tendency as somewhat declined. Second, while declining wetness may encourage farmers to migrate, it may also induce them to change what they do within rural areas including a move to non-farm occupations. As noted earlier for Africa, in recent years there has been a strong shift within the rural sector towards non-farm activities and climate change could have contributed to this. Finally, while increasing wetness around cities may slow migration, it may still promote urban income growth as a large share of rising agricultural incomes may be spent in cities.

5.1. Do farmers migrate to a primate city, not just locally?

To what degree will changing climate in a district induce people to leave the district and migrate to the primate city, often the national capital? We might not expect large effects. Those districts with more limited urban opportunities for local migration may be precisely those districts where potential migrants are likely to have the information and resources to migrate longer distances. Of course, as the third extension will suggest, adverse climatic conditions in a rural area will also have a negative impact on local towns and local urban opportunities. This is especially the case in those parts of Africa where local towns are relatively small and act largely as service centers for the hinterland. With few economic opportunities in nearby towns, migrants may instead decide to move to the national or regional primate city.

Testing this hypothesis at the sub-national level is difficult because data limitations are compounded. The small number of primate cities (see Annex 1) precludes estimation using the long difference observations and using country fixed effects would reduce sample size further. We therefore report panel data results only and use the annual average growth rate of the national population to control for country specific conditions. The dependent variable for the regression reported in Table 5 is the average annual inter-censal population growth rate of the primate city population, defined as either the district where the capital city is located or an agglomeration of 2-3 districts where the primate city-district has spilled over into neighboring districts, based upon night lights images. Defining the area of the primate city more broadly captures the true metropolitan region. This is important in Africa where migrants tend to settle at the fringe of metropolitan regions, not the central district. In the regression, the independent variable is a summary measure of the change in wetness in non-primate city districts in the country. The measure is the sum of the annualized growth rates of wetness within the district weighted by the initial period (first census) share of the district of the total population of the country in non-primate city districts.

Results in Table 5 provide some evidence that a wetter climate in the rest of the country retards primate city growth. However, the sample sizes are small and at most results are significant at the 10 percent level. Moreover controlling for overall country population growth tends to weaken the effect. For arid countries in column 4, a one standard deviation increase in growth of wetness lowers the growth rate of the primate city by 0.0031 from a mean of 0.045, a modest 7% reduction. Obviously the experiment is limited and while the results are suggestive, they do not provide strong evidence that changes in climate in the hinterlands heavily promote longer distance migration to the primate city of a country.

Table 5: Migration to primate city, panel, all countries and arid countries

Dependent variable: Annualized growth rate of primate city population

	All countries (smooth 3, lag 4)		**Arid countries** (smooth 3, lag 4)	
Weighted average growth in wetness	-0.353*	-0.295	-0.421*	-0.293*
	(0.184)	(0.186)	(0.223)	(0.151)
Annualized growth rate in national population		0.945**		0.889
		(0.432)		(0.546)
Constant	0.0438***	0.0178	0.0436***	0.0202
	(0.00224)	(0.0118)	(0.00335)	(0.0139)
N [districts]	35	35	21	21
R-squared	0.069	0.230	0.110	0.282

Robust standard errors clustered at district level; *** p<0.01, ** p<0.05, * p<0.1
Note: The 1969 census for Zambia is removed due to missing population data.

5.2. Occupational choices within rural areas

Migration, whether temporary or permanent, is not the only possible response to adverse climate fluctuations or long term changes. Drier growing conditions will lower the returns to farming and farmers may switch to non-farm activities or, especially for women, decide to drop out of the work force altogether. In the analysis described in this section we find evidence of both. These possible responses must again be seen in the overall context of climate changes in a predominantly rural economy. As noted above, if farm incomes drop, there will be less money in the rural economy, so alternative work opportunities may be scarce. This will mute the expected response of occupational choice to changes in climatic conditions.

5.2.1 Data and specifications

We test whether changes in climate have an impact on occupational choice within rural areas using individual-level data from the Demographic and Health Surveys (DHS, Macro International). DHSs use a two-stage sampling strategy, first randomly selecting enumeration areas in a country and then surveying about 30 randomly selected households in each. The surveys oversample female household members since one of the primary purposes is to collect data on reproductive health. We compile DHS data from multiple waves for each of 20 African countries maximizing overlap with our urbanization dataset (Annex 3). In total we use 53 surveys with the earliest from 1991 and the latest from 2011, and only include people in the rural sector. We examine the decision to work in agriculture versus in another rural occupation.

This look at occupational choice starts with the sub-set of people who work. Most males and females in the relevant age bracket (15-49) do work but the percentages are only 83% and 66% respectively for our sample. We don’t think of this as the usual selection problem of whether to work or not and, if so, what occupation to choose based on wage differentials. Working is closely tied to the farm and occupational choice on non-wage factors especially for females who do a lot of child and household care. We also do not have (and do not conceive of) relevant variables that affect the decision to work or not but do not affect occupational choice, in order to carry out a selection analysis. Finally, doing a comprehensive study of intra-family dynamics and choices is beyond the scope of this study. Rather we are looking for the reduced form effects of rainfall. Thus after looking at the occupational choice of whether to work, we will estimate a multinomial model where people face the choices of not work, work in agriculture, or work in non-agriculture.

Our formulations are separately estimated for women and men aged 15-49 (reducing the sample to the 25-49 age group to include only respondents who have completed all possible education does not change results). Sample size varies between 95,764 (for men in the farm/non-farm regression) and 345,840 (for women working vs. not working). All DHSs used in our study are geo-referenced, so deriving climate data for each cluster is straightforward.

A complication is that subsequent rounds (or waves) of the DHS do not survey the exact same clusters and the number of clusters increases over time. To overcome this problem we create “super-clusters” by matching each cluster in subsequent years to the geographically closest cluster in the first round survey. So super-clusters contain anywhere between 1 (in the initial round) and 26 DHS clusters. Over 70 percent contain 1 cluster, and the mean is 1.62 clusters per super-cluster. Including or dropping a small number of clusters that are far (>50km) from the original cluster location does not affect the results. Annex 4 shows the summary statistics of all variables used. Men are more likely to work in agriculture (72 percent vs. 65 percent) and more likely to work overall (83 percent versus 66 percent). The average age of respondents is between 28 and 29 for both men and women. Men generally have better education with between 63 and 68 percent reporting at least primary school versus about 50 percent for women.

Our first focus is on the choice to work in farm versus non-farm activities, the binary choice variable y_{icjt}, which we estimate as a linear probability model. How do we specify the estimating equations? To identify climate effects on occupational choice we need to control for time invariant (over the 25 years of our data) local conditions which might affect occupational choice and could be systematically correlated with climate. We also want to control for changing conditions that affect occupational choice and could also be correlated with climate. For example, in dry areas that are further drying out, non-farm opportunities may be limited and there may be low probabilities of non-farm work per se, so simple correlations would suggest a negative association between drying out and non-farm work. Thus we want to identify causal effects by within cluster changes in occupation in response to differential climate changes. We have two specifications for the occupational choice models, which are identical except for the way they control for country level conditions:

$$y_{icjt} = \alpha_0 x_{icjt} + \alpha_1 z_{jt} + \beta W_{cjt} + f_c + e_{icjt} \qquad (3)$$

$$y_{icjt} = \alpha_0 x_{icjt} + d_{jt} + \beta W_{cjt} + f_c + e_{icjt} \qquad (4)$$

where variables are defined as

y_{icjt} : binary outcome for individual i in super-cluster c, in country j and year t

i.e., work in agriculture vs. non agriculture in the rural sector; work or not work,

x_{icjt} : individual characteristics: age (and age squared) and education dummies,

z_{jt} : country characteristics in year t, national population, per capita PPP GDP and urban share,

W_{cjt} : average wetness over the three previous years,

f_c : super-cluster fixed effect,

d_{jt} : country-year fixed effect, and

e_{icjt} : error terms clustered at the DHS cluster-year level.

Both equations (3) and (4) and all estimations have super-cluster fixed effects, f_c, which control for time-invariant local socio-economic conditions influencing occupational choice, as suggested in the example in the above paragraph. However we also need to deal with time varying conditions affecting occupational choice, such as national structural change, which also might be influenced by national climatic conditions. In the first specification in equation (3), in addition to time (date of survey) effects, we control for national conditions, z_{jt}, likely to impact occupational choice overall: national population, real GDP per capita, and urban shares. For the second we use a more comprehensive approach: country-year fixed effects, d_{jt}. The potential problem with this latter approach is attenuation bias. Identification must now come from within-country cross-cluster variation in the time patterns of occupational choice and climate. We find that results, reported for both below, are quite similar for women but not men.

We control for predetermined individual characteristics of age and education, x_{icjt}, as well as differentiating effects by sex. However we do not include controls for adult marriage status, number of children or other household level indicators that could plausibly be affected by climate and instead estimate a reduced form model of climate impacts on occupational choice.

For the climate variables, we still smooth modestly over 3 periods to remove noise but have just a one year lag. Given the differential timing of surveys within a calendar year, we start with the prior year's climate, since this year's climate may yet to have an effect. We don't use longer lags because time spacing in the panel is often very short. We also expect that occupational changes may be short term and possibly represent a temporary adaptation to more recent climatic fluctuation that helps avoid the more costly and risky decision to migrate to an urban area. For women, in particular, who may have less attachment to a specific occupation and drop in and out of the labor force, responses may be immediate. As in the urbanization regressions, we estimate with the complete panel data set of all inter-DHS periods and a 'long-difference' version where each observation is based on the first and last DHS, provided they were at least 10 years apart, and 'differencing' is through super-cluster fixed effects.

Table 6 shows estimation results from a linear probability model of the choice of working in agriculture versus in a non-farm rural occupation. The table shows the results of both specifications for controlling for time varying country conditions in the panel data set. For the long difference data set, we only report country-year fixed effects results. In the long difference, given DHS samples are at different times, we want to control for time effects, if only because DHS surveys and the exact wording and frame of questions differ some over time. Because of the spread of DHS timing across countries, if we add all three country conditions to beginning and ending time effects, results turn out to be identical to the country-year fixed effect specification. Again attenuation may be an issue and we report how results are affected with just a control for time effects (always in addition to super-cluster effects).

Table 6: Probability of working in agriculture versus in another rural occupation

	Men			Female		
	Panel	Panel	Long difference	Panel	Panel	Long difference
Average Wetness (L1-L3)	0.0328	0.0356*	0.0165	0.0403**	0.0482**	0.0646**
	(0.0220)	(0.0210)	(0.0346)	(0.0195)	(0.0188)	(0.0281)
Age	-0.0180***	-0.0182***	-0.0245***	-0.00417***	-0.00420***	-0.00820***
	(0.00113)	(0.00113)	(0.00159)	(0.000721)	(0.000722)	(0.000964)
Age^2	0.000279***	0.000281***	0.000376***	7.73e-05***	7.77e-05***	0.000132***
	(1.74e-05)	(1.74e-05)	(2.47e-05)	(1.11e-05)	(1.11e-05)	(1.50e-05)
Primary education	-0.0903***	-0.0906***	-0.0732***	-0.0755***	-0.0755***	-0.0706***
	(0.00432)	(0.00432)	(0.00604)	(0.00355)	(0.00355)	(0.00501)
Secondary education	-0.216***	-0.216***	-0.181***	-0.247***	-0.248***	-0.238***
	(0.00648)	(0.00649)	(0.00954)	(0.00634)	(0.00635)	(0.00941)
Higher education	-0.544***	-0.545***	-0.536***	-0.518***	-0.517***	-0.519***
	(0.0112)	(0.0112)	(0.0194)	(0.0116)	(0.0116)	(0.0173)
ln(nat'l population)		0.219**			0.897***	
		(0.103)			(0.106)	
ln(nat'l GDP per cap. PPP)		-0.0588*			-0.140***	
		(0.0305)			(0.0324)	
Nat'l urban share		0.00266			0.00836**	
		(0.00278)			(0.00330)	
Observations	95,764	95,764	41,449	229,250	229,250	124,322
R-squared	0.276	0.274	0.289	0.330	0.329	0.330
Countries	19	19	10	20	20	12
Country-years	50	50	20	52	52	24
Superclusters	3567	3567	1898	3775	3775	2260
Supercluster-years	7553	7553	3228	8184	8184	3955
Fixed effects	country* year	year	country* year	country* year	Year	country* year

Notes: Errors clustered by supercluster-year; each specification includes supercluster fixed effects.
*** p<0.01, ** p<0.05, * p<0.1

The main variable of interest—average wetness in the three years prior to the survey—is consistently positive and significant for women in columns 4-6 across the 3 specifications in Table 6. Increased wetness means, conditional on working, females are more likely to work in agriculture, than in non-farm activities. The long difference effects are stronger; and, for that, a (levels) standard deviation increase in wetness (about 0.5) leads to an increased probability of working in farm activity by 0.032, noting the probability is already high at 0.65. As noted earlier, if we increase from its minimum to maximum value, that increases the probability of working in farm activity by over 0.20. If for the long difference we replace country-time fixed effects by time effects to reduce attenuation bias, the coefficient for women increases by about 25%. For men, results are weak and only significant at the 10% level in the panel formulation without country-year fixed effects. Altering the specification for the male long difference produces no significant effects. Conditional on being in the rural sector, males seem less responsive to climate change. It may be male decisions are more over whether to migrate or not, but if at home whether they work the land or not is not responsive. It is women who adjust.

Control variables have expected effects: the more education and the younger they are, the less likely people are to work in agriculture. On age the turning point in the quadratic is about 32 years, noting the mean age is less than that. Increases in national population and declines in per capita income are both associated with a greater chance overall of working in agriculture.

On the decision to work or not in Table 7, again results for females are more robust and pronounced. A one standard deviation increase in the level of wetness is associated with about a 0.02 increase in the probability of working in the panel country-year fixed effect and long difference specification. For men again, we only find this positive effect in the panel formulation without country-year fixed effects and just controls on country conditions and year effects.

Overall, more favorable agricultural conditions make it more likely for women to be working and, if working, to be engaged in agriculture. Conversely, drier conditions seem to motivate women to leave agriculture or to leave the rural work force altogether. For men, these results only apply to the more flexible panel specification where we control for country conditions and years not country-year fixed effects. Results are consistent with a model that sees women dropping out of agricultural work or even out of the work force as agro-climatic conditions deteriorate. When conditions improve, both in the fields and by extension in the non-farm sector, women are more likely to leave household work behind to engage in farming or other rural occupations. Men are perhaps more likely to continue farming even under adverse conditions possibly to maintain their hold on land or because of a lack of alternatives.

Table 7: Probability of working in any rural sector versus not working

	Men			Female		
	Panel	Panel	Long difference	Panel	Panel	Long difference
Average Wetness (L1-L3)	-0.0103	0.0575***	-0.0100	0.0413***	0.0346***	0.0412**
	(0.0104)	(0.0115)	(0.0142)	(0.0126)	(0.0125)	(0.0172)
Age	0.0647***	0.0650***	0.0562***	0.0434***	0.0432***	0.0416***
	(0.00108)	(0.00108)	(0.00149)	(0.000739)	(0.000740)	(0.00109)
Age^2	-0.00089***	-0.00089***	-0.00078***	-0.00056***	-0.00056***	-0.00054***
	(1.54e-05)	(1.55e-05)	(2.15e-05)	(1.10e-05)	(1.10e-05)	(1.60e-05)
Primary education	-0.0290***	-0.0294***	-0.0185***	0.0123***	0.0124***	0.0246***
	(0.00295)	(0.00297)	(0.00429)	(0.00295)	(0.00297)	(0.00419)
Secondary education	-0.129***	-0.128***	-0.105***	-0.0737***	-0.0739***	-0.0825***
	(0.00427)	(0.00430)	(0.00696)	(0.00456)	(0.00458)	(0.00669)
Higher education	-0.0739***	-0.0740***	-0.0136	0.0596***	0.0613***	0.0159
	(0.00998)	(0.00998)	(0.0149)	(0.0127)	(0.0127)	(0.0163)
ln(nat'l population)		0.456***			0.844***	
		(0.0853)			(0.0858)	
ln(nat'l GDP per cap. PPP)		-0.300***			-0.124***	
		(0.0238)			(0.0306)	
Nat'l urban share		-0.0111***			-0.00827***	
		(0.00223)			(0.00249)	
Observations	115,563	115,563	48,337	345,840	345,840	184,174
R-squared	0.372	0.358	0.357	0.272	0.267	0.257
Countries	19	19	10	20	20	12
Country-years	50	50	20	52	52	24
Super-clusters	3602	3602	1904	3784	3784	2264
Super-cluster-years	7703	7703	3258	8245	8245	3969
Fixed effects	country* year	year	country* year	country* year	year	country* year

Notes: Errors clustered by super-cluster-year; Each specification includes super-cluster fixed effects.
*** p<0.01, ** p<0.05, * p<0.1

5.3. Does increasing rainfall raise city incomes?

Even if favorable climatic conditions retard urbanization by making it less likely for rural residents to leave the countryside, in some situations, we may expect spillovers to nearby cities and towns. Towns which serve as market and service centers for their hinterlands are likely to benefit if their agricultural hinterland does well. Good growing conditions induce farmers to spend some share of their additional income on urban consumption and investment goods (such as improved seeds or farm equipment), raising returns to living in cities. This would suggest that the migration responses we estimated earlier are muted relative to a situation where there are no rural-urban synergies. Of course if the nearby city is primarily engaged in manufacturing production for export with little market connection to its hinterland, then improved conditions in agriculture just have a full rural to urban migration impact.

Data on income or city product are not consistently available for African cities, so we resort to using an indirect measure. Following the approach outlined in Henderson, Storeygard and Weil (2012), we test whether the intensity of nighttime light emitted by the city is affected by the amount of rainfall within a 30 km radius around each city in the current or prior years (see Figure 5). The nighttime lights data come from the U.S. Defense Meteorological Satellite Program (DMSP), a weather satellite system that captures visible light during nighttime overpasses. We use data from 1992 to 2008 at the grid cell level with a resolution of 0.86 km. The data product typically used for socioeconomic analysis contains only stable lights after temporary light sources such as forest or savannah fires and gas flares have been removed (e.g., Elvidge, Baugh, Kihn, Kroehl and Davis 1997). Light intensity for each pixel is expressed as a "digital number" linearly scaled between 0 and 63 which we use as the dependent variable in a regression on rainfall. We use rainfall rather than wetness in this analysis because it is hard to get temperature measures at such fine resolution that do not heavily rely on interpolation of sparse data.

Our analysis includes 1,158 cities and towns in Africa for which a population estimate was available from a comprehensive census database (citypopulation.de) and whose location corresponds to a lit area in the DMSP data set. The city's "total amount" of light for each year is the sum of the digital number (light intensity) over all grid cells that fall within the outer envelope—or maximum extent—of the city light footprints across all years (see Figure 3). Rainfall measures are from the University of Delaware data set as before. For each city, the annual average of daily rainfall totals is averaged over the grid cells that fall within a 30 km radius from the city center.

Our specification is:

$$\ln(light_{ict} + 1) = \sum_{j=0}^{k} \beta_j \ln rain_{ic,t-j} + \emptyset_i + \lambda_t + \alpha_c t + \varepsilon_{ict} \qquad (5)$$

where variables are defined as

$light_{ict}$: per pixel light digital number summed over all pixels in city i, country c, in year t,

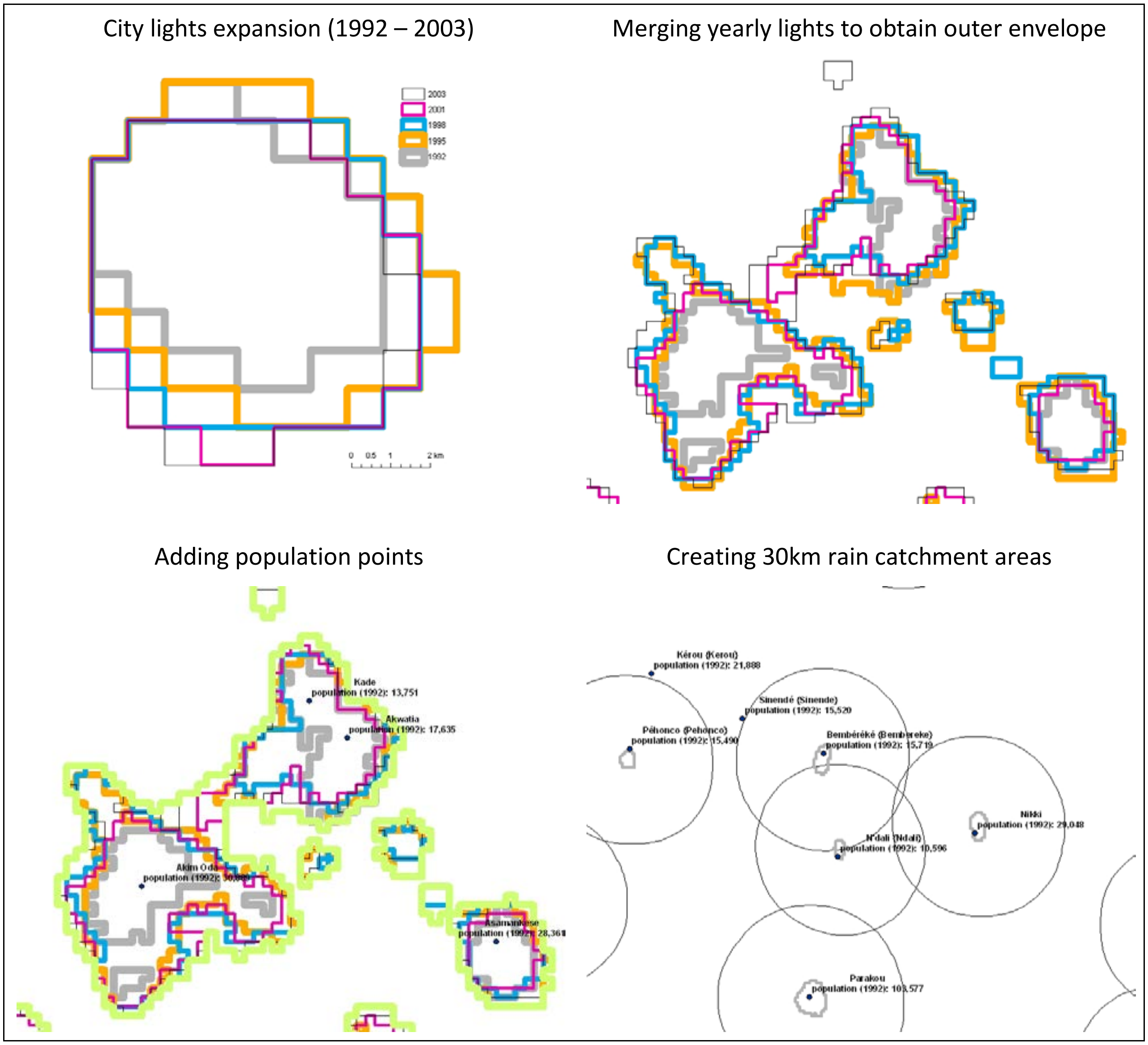
$rain_{ict}$: average rainfall in millimeters per day within 30 km of city i, current or lagged ,

$\emptyset_i$ and λ_t : city and time fixed effects, and

α_c : country growth trend given the annual series.

Equation (5) is an annual panel specification for cities. To identify rainfall effects on lights, we control for city conditions, for time effects (to account for annual differences across and within satellites in effective sensor settings), and country-specific growth trends.

Figure 5: Spatial data integration to obtain city level lights and rain catchment data



We find that the impact of rainfall in the current year and in some cases the previous year has a very different impact on the city income proxy in countries with a high dependence on agriculture versus low dependence. We set the threshold for high dependence as having a national agricultural share of GDP of

20 percent or more in 2000, but obtain similar results at 25 percent. For countries where farming is more important, increased rainfall increases light intensity presumably because of added spending by farmers in local urban areas. This effect appears to more than offset the effect of climatic conditions on population movements as reported earlier. In Table 8, the elasticity of city lights with respect to rainfall ranges from 0.075 to 0.145 depending on the precise specification. Column 2 shows a smaller one year lagged effect in addition to the contemporaneous effect, but column 3 suggests there is a limited potential lag structure. In columns 4 and 5 we worry that high rainfall could lower electricity prices in countries with a high share of hydropower plants or, more specifically, in cities more likely served by nearby hydropower. However, using data on national electricity generation and the location of power plants from World Bank (2010), we find no significant effects, possibly because tightly regulated electricity prices in many African countries mute any such possible influence. In column 6, we show that better rainfall does not have a significant effect on lights in cities greater than 50,000 population in our base year. These will be cities with a more diversified economic base, including manufacturing and administrative government functions. Productivity gains in their rural hinterland may have little effect on the city economy.

In the much smaller set of cities (204 vs. 954) in countries with lower dependence on the agricultural sector we find very different results (Table 9). Increasing rainfall appears to have a negative impact on lights. There does not appear to be an income effect through agricultural productivity in these countries that are presumably less dependent on spending by local farmers. As in our prior analysis, better agro-ecological conditions in the hinterland retard urbanization and the city's access to local labor.

Table 8: Light intensity in high agricultural dependence countries (agriculture share in GDP more than 20 percent)

	(1)	(2)	(3)	(4)	(5)	(6)
ln *rain*(t)	0.0754**	0.1000***	0.0924***	0.145*	0.102	0.107**
	(0.0359)	(0.0338)	(0.0356)	(0.0753)	(0.0654)	(0.0440)
ln *rain*(t-1)		0.0565*	0.0312			
		(0.0337)	(0.0328)			
ln *rain*(t-2)			0.00739			
			(0.0337)			
ln *rain*(t) * hydrofrac > 40				-0.0921		
				(0.0856)		
ln *rain*(t) * hydro close					-0.0371	
					(0.0860)	
ln *rain*(t) * pop1992 > 50k						-0.137*
						(0.0829)
observations	16,217	15,263	14,309	16,217	13,429	16,217
R-squared	0.256	0.197	0.186	0.256	0.259	0.256
cities	954	954	954	954	790	954
sample	ag>20	ag>20	ag>20	ag>20	ag>20	ag>20
years	92-08	93-08	94-08	92-08	92-08	92-08

All specifications contain city and year fixed effects, and country-specific linear time trends.
Robust standard errors in parentheses.*** p <0.01, ** p<0.05, * p<0.1.

Table 9: Light intensity in low agricultural dependence countries (agriculture share in GDP less than 20 percent)

	(1)	(2)	(3)	(4)	(5)	(6)
ln *rain*(t)	-0.108***	-0.134***	-0.132***	-0.0905*	-0.0573	-0.106***
	(0.0384)	(0.0445)	(0.0371)	(0.0491)	(0.0481)	(0.0400)
ln *rain*(t-1)		-0.0631*	-0.0708*			
		(0.0376)	(0.0366)			
ln *rain*(t-2)			0.066			
			(0.0419)			
ln *rain*(t) * hydrofrac > 40				-0.0319		
				(0.0750)		
ln *rain*(t) * hydro close					0.066	
					(0.179)	
ln *rain*(t) * pop1992 > 50k						-0.0159
						(0.0912)
observations	3,468	3,264	3,060	3,468	2,193	3,468
R-squared	0.35	0.371	0.363	0.35	0.314	0.35
cities	204	204	204	204	129	204
sample	ag<20	ag<20	ag<20	ag<20	ag<20	ag<20
years	92-08	93-08	94-08	92-08	92-08	92-08

All specifications contain city and year fixed effects, and country-specific linear time trends.
Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

6. Conclusions

With a high dependence on agriculture and an already highly variable and often marginally suitable agro-climate, Africa may be at higher risk from climate change than most other world regions. Agricultural adaptation through improved seeds and increased irrigation will be one possible response. But technological change in Africa has been slow and, despite frequent droughts in the past, irrigation infrastructure remains scarce. So for many farmers facing adverse climatic conditions the only option may be to migrate to urban areas.

Our analysis suggests that agro-climatic conditions do indeed influence urbanization rates, with better conditions retarding urbanization and unfavorable years leading to greater urban population growth. These effects appear to be stronger for local cities than for national primate cities suggesting that farmers, who often have limited resources, move to nearby cities first, in some cases probably temporarily. We also find some evidence of alternative adaptation strategies in that rural residents are more likely to work in the non-farm sector when growing conditions have been unfavorable. Women are more likely to drop out of the labor force altogether when times are tough. Finally, we find some evidence that improved conditions for agriculture raise local urban incomes presumably through local spending by farmers, but only in countries with a high dependence on agriculture.

These results confirm the strong link between climatic conditions and urbanization, adding to the growing economic literature on climate and development. Our results suggest that more severe and persistent climate changes, which will likely increase the challenges faced by Africa’s farmers, could further accelerate migration to cities. Even though migration is only one contributor to urban growth—relatively high urban fertility is a larger factor—faster migration rates could overwhelm many African cities that already struggle to absorb a rising population into productive jobs. Effective global climate change mitigation remains elusive and an increase in global average temperature possibly far in excess of 2° Celsius seems increasingly likely. Strong support for agricultural adaptation and for more effective urban management is therefore becoming an even more urgent priority.

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Annex 1: Countries included in the data set with summary information

Country	**Districts encompassing primate cities**	**LD, panel or both**	**Arid country**	**Census years (number of districts)**
Benin	Antlantique, Oueme	Both	Yes	1979, 1992 (6), 2002 (6)
Chad	Chari-Baguirmi	Both	Yes	**1964**, 1993, 2009 (14)
Cameroon	Littoral, Centre	Both	No	1976, 1987 (7), 2005 (7)
Ethiopia	Addis, Oromia	Panel	Yes	1994, 2007 (11)
Ghana	Greater Accra, Western, Eastern	Both	Yes	1960, 1970 (7), 1984 (7), 2000 (7)
Kenya (1)	Nairobi , Kiambu, Muarang'a	Both	No	1969, 1979 (31), 1989 (39)
Kenya (2)	Nairobi , Kiambu, Muarang'a	Panel	No	1999, 2009 (40)
Liberia	Bomi	LD	No	**1962**, 1974, 2008 (8)
Mali	Bamako, Koulikoro	Both	Yes	1976, 1987 (7), 1998 (7), **2008**
Mozambique	Maputo, Province of Maputo	Both	Yes	1980, 1997 (10), **2007**
Malawi	Blantyre, Lilongwe	Both	No	1966, 1977 (23), 1987 (23), 1998 (23), 2008 (23)
Niger	Niamey	Both	Yes	1977, 1988 (7), 2001 (7)
Sudan	Khartoum, Blue Nile	Both	Yes	1973, 1983 (9), 1993 (9)
Senegal	Dhakar, Thies	Both	Yes	1976, 1988 (8), 2003 (8)
Tanzania	Dar, Pwani	Both	Yes	1967, 1978 (17), 1988 (20), 2002 (20)
Uganda	Kampala, Kayunga	Both	No	1969, 1980 (17), 1991 (18), 2002 (18)
Zambia	Lusaka	Both	No	1969, 1980 (6), 1990 (9), 2000 (9)
Zimbabwe	Mashonaland, East & West	Both	Yes	1982, 1992 (8), 2001 (8)

Notes:
1. Census years in bold dropped from data set due to missing urban data in many/all districts.
2. Mali is missing urban data for one district in 1987, but not for 1976 or 1998. Hence, this district is included in the long difference, but not in the panel.

Annex 2: A model of district level urbanization

In a district, we assume people move between the rural sector and local town/city to equalize incomes, or so that

$$I_a = p_a A_a g(\bar{K}/(\bar{N}-N),W) = I_u = A_u f(N), \quad g_1, g_2 > 0,\ f_N(N; N > N^*) < 0 \tag{1}$$

where I_a is per person rural income and I_u urban income. For rural income, p_a is the price of agricultural output set in world markets. A_a is the level of technological development which might be related to human capital accumulation, $\bar{K}/N_a$ is the land to labor ratio in the sector and W is wetness. Increased wetness improves yields. Farmers are assumed to each have an equal claim on returns from land as under, for example, communal based land ownership in Africa (Bruce 1998). As such, they receive their average product as specified in (1).

Total population of the district, $\bar{N}$, is divided between the urban and rural sectors, or

$$N_a = \bar{N} - N \tag{2}$$

where N is the urban population. In urban models of a city, there are external scale economies in production that generate initial benefits to having a larger city, but there are also diseconomies in terms of potential work time that is lost in commuting, which increase as city population and spatial area rise. Such models with a residential sector spatial equilibrium yield a reduced form for per person urban real income to be spent on food and urban products (Duranton and Puga, 2004). In equation (1), the price of the urban good is the numeraire and A_u is the technology level in the city which again may be a function of human capital accumulation. $f(N)$ is assumed to be an inverted-U shaped function of city population, which achieves its maximum at N^*. Here, as we will see later, as the urban population expands relative to rural, for stability we need to assume that the rate of growth of urban incomes is less than that of rural incomes.

Our estimating equation is based on a differenced version of (1). We define:

$$M \equiv d[p_a h_a^{\theta_a} g(\bar{K}/(\bar{N}-N),W) - h_u^{\theta_u} f(N)]/dN > 0 \tag{3}$$

M is positive in a stable allocation between the urban and rural sectors. That is, as the urban sector expands, the rise in productivity in the rural sector from an increased capital-labor ratio, $\bar{K}/(\bar{N}-N)$, exceeds that in the urban sector, which, under the assumption that $N \geq N^*$, is less than or equal to zero.

In our estimating equation we look at the change (or growth) in the urban share over time or $d(N / \bar{N})$. Differencing (1) we have

$$d\frac{N}{\bar{N}} = M^{-1}\bar{N}^{-1}\left[[p_a A_a g_1(\cdot)\frac{\bar{K}\bar{N}}{(\bar{N}-N)^2} - MN]\frac{d\bar{N}}{\bar{N}} - p_a A_a g_2(\cdot)\frac{W}{(\bar{N}-N)}\frac{dW}{W} + p_a A_a g(\cdot)\{-\frac{dp_a}{p_a} + [\frac{dA_u}{A_u} - \frac{dA_a}{A_a}]\} \right] \quad (4)$$

While $dN / d\bar{N} > 0$, the effect on the urban share, $N / \bar{N}$, of an increase in district population is ambiguous. Everything else is straightforward. An increase in the relative price of the agricultural good decreases urbanization, because the enhanced returns to agriculture draw people out of the urban sector. For technology, as in growth models of the urbanization process, we generally assume $dA_u / A_u \geq dA_a / A_a$, so technological progress favors the urban sector. The key item for us concerns wetness. Increased wetness leads to a decline in the share urban. In the specification of an estimating equation we use country-time fixed effects to control for changes in technology, relative prices, and overall population growth. Our focus will be on changes in wetness and other climate measures, as well as items that may affect effective land usage like irrigation.

What is omitted from the model is the potential for inter-district migration, whereby people will leave the rural sector of the district and move to a primate of other major city. Also the model does not capture the synergy between the urban and rural sectors. Local farmers will utilize retail and other “non-traded” services of the city as they import manufactured products from abroad or the capital city and export food products. Finally the model does not capture non-farm activity in the rural sector. In Africa traditionally non-farm rural sector activity comprised less than 10% of rural employment. However that is changing rapidly and the share of non-farm activity in the rural sector is expanding. In the empirical analysis we explore these aspects.

Annex 3: DHS data sets used in the occupational choice analysis

Country	Years
Benin	1996, 2001
Burkina Faso	1992-1993, 1998-1999, 2003, 2010-2011
Cameroon	1991, 2004, 2011
Cote d'Ivoire	1994, 1998-1999
Ethiopia	2000, 2005, 2010-2011
Ghana	1993-1994, 1998-1999, 2003, 2008
Guinea	1999, 2005
Kenya	2003, 2008-2009
Lesotho	2004-2005, 2009-2010
Liberia	1986, 2006-2007
Malawi	2000, 2004-2005, 2010
Mali	1995-1996, 2001, 2006
Namibia	2000, 2006-2007
Niger	1992, 1998
Nigeria	2003, 2008
Rwanda	2005, 2010-2011
Senegal	1992-1993, 1997, 2005, 2010-2011
Tanzania	1999, 2009-2010
Uganda	2000-2001, 2006, 2011
Zimbabwe	1999, 2005-2006, 2010-2011

Annex 4: Summary statistics for occupation choice analysis

	Working vs. not working						
	Women, n = 345,840				**Men**, n = 115,563		
	Mean	Std. Dev.	Min	Max	Mean	Std. Dev.	Min
Working	0.662	0.473	0	1	0.827	0.379	0
Age	28.612	9.586	15	49	28.497	9.840	15
Education							
Primary	0.358	0.479	0	1	0.418	0.493	0
Secondary	0.142	0.349	0	1	0.240	0.427	0
Post-secondary	0.009	0.094	0	1	0.025	0.155	0
Avg. wetness	0.849	0.490	0.015	3.491	0.847	0.475	0.015
Ln(pop)	16.743	1.009	14.455	18.831	16.794	1.068	14.455
Ln(p.c. GDP, PPP)	6.953	0.493	5.765	8.607	6.932	0.559	5.765
Urban pop share	28.333	11.795	12.08	52.1	28.994	12.444	12.08

	Working in agriculture vs. other occupation						
	Women, n = 229,250				**Men**, n = 95,764		
	Mean	Std. Dev.	Min	Max	Mean	Std. Dev.	Min
Agriculture	0.651	0.477	0	1	0.716	0.451	0
Age	29.998	9.421	15	49	29.944	9.553	15
Education							
Primary	0.374	0.484	0	1	0.413	0.492	0
Secondary	0.113	0.317	0	1	0.200	0.400	0
Post-secondary	0.010	0.100	0	1	0.026	0.158	0
Avg. wetness	0.892	0.490	0.015	3.491	0.849	0.480	0.015
Ln(pop)	16.745	0.916	14.455	18.831	16.868	1.034	14.455
Ln(p.c. GDP, PPP)	6.950	0.433	5.765	8.607	6.940	0.514	5.765
Urban pop share	28.022	11.779	12.08	52.1	28.662	12.645	12.08

Annex 5. Summary statistics for night-lights sample

						Countries where share agriculture in			
			All				exceeds 20%		
Variable	Obs	Mean	Std. Dev.	Min	Max	Obs	Mean	Std Dev	min
Ln (average rainfall within 30 km of the city light (excluding the light itself; meters/year))	19685	0.701	0.689	-8.59	2.47	16217	0.794	0.601	-8.59
ln(lights digital number + 1)	19685	4.75	2.65	0	12.09	16217	4.45	2.63	0
dummy: population in 1992 is over 50,000	19685	0.249	0.432	0	1	16217	0.264	0.441	0
dummy: a city's nearest power plant is hydroelectric (if both available in country)	15622	0.482	0.500	0	1	13429	0.511	0.500	0
dummy: fraction of a country's generating capacity from hydroelectric facilities is over 0.4	19685	0.649	0.477	0	1	16217	0.714	0.452	0
fraction of national GDP from agriculture in 2000	19685	32.66	14.47	2.70	72.01	16217	37.51	10.56	20.26