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Has climate change driven urbanization in Africa?

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ABSTRACT

This paper documents strong but differentiated links between climate and urbanization in large panels of districts and cities in Sub-Saharan Africa, which has dried substantially in the past fifty years. The key dimension of heterogeneity is whether cities are likely to have manufacturing for export outside their regions, as opposed to being exclusively market towns providing local services to agricultural hinterlands. In regions where cities are likely to be manufacturing centers (25% of our sample), drier conditions increase urbanization and total urban incomes. There, urban migration provides an "escape" from negative agricultural moisture shocks. However, in the remaining market towns (75% of our sample), cities just service agriculture. Reduced farm incomes from negative shocks reduce demand for urban services and derived demand for urban labor. There, drying has little impact on urbanization or total urban incomes. Lack of structural transformation in Africa inhibits a better response to climate change.

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1. Introduction

Sub-Saharan Africa (hereafter Africa) is urbanizing quickly, with cities and towns growing at an annual rate of close to four percent over the last 20 years. As of 2014, its urban population numbered nearly 350 million. 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. The longstanding debate in the literature about the relative importance of push versus pull factors in urbanization has focused recently on Africa. Papers assess 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, 2013; Gollin et al., 2015). Other papers examine push factors including civil wars (Fay and Opal, 2000), poor rural infrastructure (Collier et al., 2008), and our focus, climate variability and change (Barrios et al., 2006).

This paper analyzes the consequences of climate variability and change for African urbanization, using variation at the district and city level within countries. Over the last 50 years much of Africa has experienced a decline in moisture availability. Fig. 1 maps average moisture in the 1950s and 1960s. Moisture is measured by an index combining precipitation and potential evapotranspiration (which is a function of temperature). A moisture level under 1 indicates that there is less rainfall available than would evaporate at the prevailing temperature. This is the cut-off we use to define "arid" areas.[1] Fig. 2 shows that much of the strongest (10–50%) decline in moisture over the subsequent 40 years occurred in parts of Africa that were initially relatively dry (moisture under 0.65 or between 0.65 and 1.0 in Fig. 1), increasing the vulnerability of these already vulnerable areas. In a region with limited irrigation, this decline in moisture has surely affected agricultural productivity.

We address two related empirical questions. The first question is whether adverse changes in climate push people out of rural areas into urban areas. We find strong evidence of this push, but only in districts likely to produce manufactures that could be

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[1] We use "arid" as shorthand to also include dry-subhumid, semi-arid and hyper-arid climates (see UNEP 1992).

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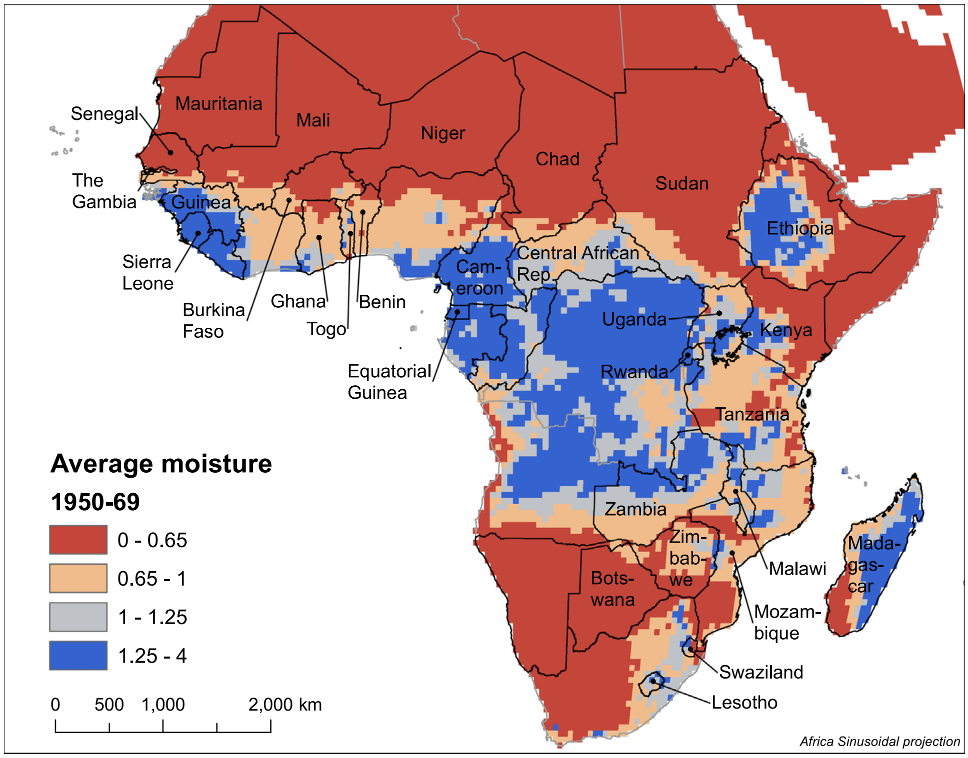

Fig. 1. Historical levels of moisture (precipitation/PET).

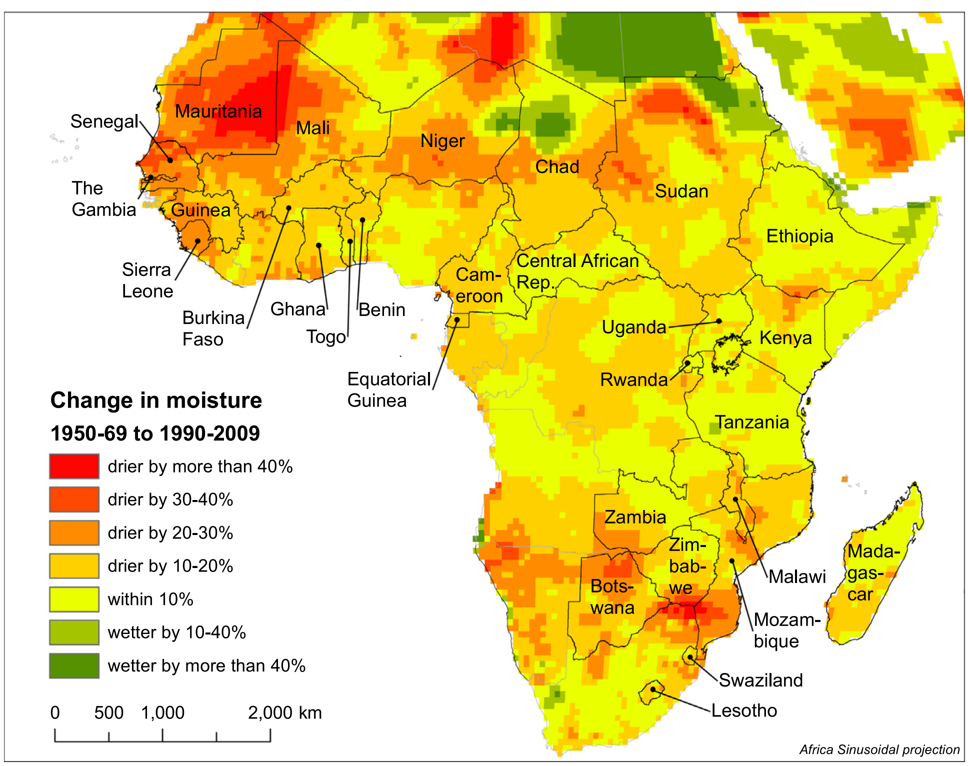

Fig. 2. Moisture in Africa 1950–69 to 1990–2009.

exported outside the district. The second question is whether that push increases the total income of local cities. We find evidence supporting this hypothesis, but again only in districts likely to produce tradable manufactures. Thus, urbanization provides an "escape" from the effect of deteriorating climate on agricultural productivity in particular contexts, but those contexts make up less than 25% of units in our sample. The message from this is simple. Spatial and structural transformation driven by climate change will only be successful where cities can absorb the excess labor. For Africa that is a challenge. According to the World

Development Indicators, between 1970 and 2000, the share of GDP in manufacturing increased in only 9 of 20 countries with relevant data. In the following decade, 21 of 34 countries with relevant data, including 16 of the original 20, saw decreases in their share of GDP in manufacturing. These decreases could be related to increased competition following removal of domestic import trade barriers and exchange rate appreciation, perhaps driven by resource price increases (Harding and Venables, 2010). In any case, by 2010 only 3 of the 34 countries had manufacturing shares over 15%, with the majority under 8%.[2]

We find consistent patterns when analyzing the effects of climate over two different temporal and spatial scales. Specifically, first we look at local, within-district urbanization for an unbalanced 50-year panel of census data for an estimating sample of 359 districts in 29 African countries. Typical intervals between censuses in the panel are 10–15 years. Second, we look annually from 1992 to 2008 at 1158 cities to see how nearby climate variability affects local city income growth as proxied by growth in night lights (Henderson et al., 2012).

Our model treats districts as small open economies that all export agricultural products to destinations outside the district and may or may not produce industrial products that are potentially tradable. In this context, climate affects urbanization only in districts that have some industry, not in districts entirely dependent on agriculture. When the local agricultural sector is competing for labor with an urban sector engaged in production of goods tradable outside the district, declines in moisture encourage urbanization by offering alternative employment for farmers. If, however, local towns exist only to provide agriculture with local services not traded across districts, then a decline in moisture has little or no effect on city population because the two sectors are not in competition for labor for tradable activity. We also might expect weaker climate effects in wetter areas where the marginal effect of reduced moisture may be less harmful to farmers.

Twenty-three percent of districts in our sample show evidence of an industrial base, and those are divided almost equally between non-arid areas and arid ones where we might expect stronger effects. For the most industrialized areas, a one standard deviation increase in moisture growth reduces urbanization by 0.016, or 52% of the mean growth rate in share urban. Moving from the minimum to maximum (trimmed) growth in moisture implies a decrease in the urban share growth rate of 0.093, three times the mean urban share growth rate.

We then consider whether adverse changes in climate stimulate the development of the urban sector and raise total urban income. The answer again depends on whether the district is industrialized. If so, total income rises with a decline of moisture (due to in-migration). However if cities only exist to serve agriculture, then a decline in moisture generally leads to either no effect or a decline in total city income. For cities most likely to have a manufacturing export base, the point estimate of the elasticity of lights with respect to rainfall is about -0.17. When cities are likely to just provide services to farmers, the point estimate of the elasticity is very close to zero. Thus given the lack of widespread industrialization in much of Africa, most districts do not respond to climate deterioration with increased urbanization and urban incomes.

Our empirical results are reduced form estimates of the net effects of moisture on urbanization and on city incomes. We have hypothesized that the mechanism is adverse climate driving farmers into urban manufacturing. In Section 7 we explore two sets of evidence related to mechanisms. First we rule out conflict as a mechanism through which climate affects urbanization. While recent work has argued that climate affects conflict, we find no evidence that conflict is driving our results.[3] Second, we explore micro evidence on our hypothesized mechanism. We discuss strong supportive evidence from India where economic census data on manufacturing are available. For Africa such data are not available. The best we can do is to use individual-level observations from the Demographic and Health Surveys (DHS) to show how migration may be related to climate.[4] The DHS do not have the data needed to properly study climate and weather effects on rural-urban migration, but the evidence we discuss is broadly consistent with our hypothesized mechanism.

While our analysis necessarily focuses on the impacts of past climate variability, the specter of future climate change is a strong motivation. 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 by expected future climate change (e.g., Collier et al., 2008). Barrios et al. (2010) argue that unfavorable rainfall trends may have already contributed to Africa's poor growth performance over the last 40 years. While the precise pattern of future change for individual regions is highly uncertain, further drying is the most common prediction for parts of Africa. Overall, our results suggest that if future climate change will have the negative impacts on agriculture in Africa that many climate scientists and agronomists expect, there will be an increased pace of urbanization in places where towns are more industrialized, but the transition may be more problematic in less industrialized regions.

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 develops a model of how changes in climate will affect (a) the division of population between the urban and rural sector and (b) urban incomes. Section 4 describes the construction of the core climate, urbanization, and industry indicators. Other data sets used are described in the relevant empirical sections. Section 5 presents the analysis of the impact of changes in moisture availability on local urbanization. Section 6 examines the effects on urban incomes. Section 7 explores possible mechanisms. Section 8 concludes.

2. Literature on climate change and its impacts in Africa

2.1. Urbanization, local city growth and climate

The most closely related paper on climate change and urbanization in Africa is Barrios et al. (2006), who estimate an increase in the national urban share of 0.45 percent with a reduction in national rainfall of 1 percent. Henderson et al. (2013) find more imprecise effects of rainfall. Brückner (2012) uses rainfall as an instrument for agricultural GDP share in Africa and finds that a decrease in this share leads to increased urbanization. All three papers have two limitations we overcome in the present work. First, they use national data, in a context where there is significant within-country climate variation and most migration is local (Jónsson, 2010). We exploit within-country heterogeneity for a more nuanced and precise analysis of the effects of climate changes on urbanization. Second, those papers

[2] http://data.worldbank.org/data-catalog/world-development-indicators. Accessed 28 June 2015.

[3] See Burke et al. (2015) for a review of the climate and conflict literature.

[4] See Young (2013) on use of the DHS to study other aspects of migration.

examine national urbanization using population data at regular 1-, 5- or 10-year intervals. Such 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. With these new data we find effects at the local but not national level, and we find heterogeneity of effects as discussed above.

Related studies use microdata to study the effect of rainfall on migration per se, rather than urbanization. They are informative and examine issues not covered in our approach, including movement across rural areas and between countries, as well as from rural areas to cities elsewhere in the country (e.g. Henry et al., 2004) and temporary or circular movement (Parnell and Walawege, 2011).[5] These studies typically interview rural residents about their migration history, thereby omitting permanent moves to cities and relying heavily on recollected dates. We limit our scope to net effects on urbanization within districts over long time periods of climate change.

Two other papers indirectly relate to how climate change might affect African urban incomes. Jedwab's (2013) historical study of Ghana and Côte d'Ivoire suggests that conditions in agriculture have a strong effect on nearby market towns that serve them. Gollin et al. (2015) explore how natural resource income affects urban development, extending the simple two-sector model of the rural-urban divide to include multiple urban economic sectors that may be differentially affected. We will model the effect of climate change on district urban incomes using insights from these two papers.

2.2. Climate change in general

Sub-Saharan Africa has a highly diverse and variable climate. Moisture availability ranges from the hyperarid Sahara and Kalahari deserts to the humid tropics of Central Africa. In 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) phenomenon in which changes in Pacific Ocean temperatures indirectly affect African weather (Conway 2009). These processes influence temperatures and precipitation across the continent including extreme events like meteorological droughts. 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 (e.g., Collins, 2011; Nicholson et al., 2013). The pattern for recent trends in annual precipitation is more nuanced and variable, including increasing and decreasing trends in different subregions (Maidment et al. 2015).

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 some consensus about global temperature trends, regional scenarios of temperature and 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 (World Bank, 2013). In general, average summer temperature is expected to increase by 1.5 °C by 2050 in Africa under an optimistic (2 °C) global warming scenario. The area exposed to heat extremes is expected to expand to 45 percent of the region by 2050.[6] Under a more pessimistic (4 °C) global scenario, these trends would be exacerbated. Falling precipitation and rising temperatures would likely worsen agricultural growing conditions in large parts of Africa, especially in coastal West Africa and in Southern Africa.

A significant literature on climate change and African agriculture is emerging. The majority of studies predict 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) under more pessimistic climate scenarios (e.g., Kurukulasuriya et al. 2006, Kurukulasuriya and Mendelsohn, 2008; Schlenker and Lobell, 2010; Knox et al., 2012).[7] Assessing potential effects has been challenging in part because adaptation in agriculture appears to be more difficult in Africa. Fertilizer use, for instance, has stagnated in Africa at low levels since 1980, while it has risen tenfold in Asia and Latin America (Cooper et al. 2013), and only 4 percent of agricultural land is irrigated compared to 18 percent globally (You et al. 2010). These studies motivate some specifications we test.

3. Modeling the impact of climate variability on local urbanization

We model movement of workers between an urban and a rural sector which together comprise a district. While migration across district boundaries, for example to capital cities, clearly plays a role in this context and we consider this, our focus is on local migration, which is very important in many African countries (Jónsson, 2010). Our goal is to model the effect of a change in moisture in a district on the urban-rural division of population and on city total income, the two outcomes we can measure in the data. The model treats districts as small open economies, facing fixed prices of exports and imports to other districts or internationally. We would find more nuanced but qualitatively similar effects if districts faced finite external demand elasticities. However, we note that, if districts are treated as closed economies as in the historical spatial transformation literature, theoretical results could be quite different (see Caselli and Coleman (2001), as well as Desmet and Henderson, (2015) for a review). The context and what we find empirically fits our formulation.

The model is formally described in Appendix B. Here we summarize and highlight the essential results. In the model, the urban sector (city) produces services, which are not traded across districts; and it may or may not produce manufactures that are potentially tradable across districts. By potentially tradable we mean either some portion is exported or local production substitutes (perfectly) against imports. Services are modeled as having constant returns to scale but manufacturing as having external economies of scale as in traditional urban models. In the city, diseconomies in commuting reduce effective labor hours in employment as city size increases, in opposition to scale economies. Wages are equalized within the urban sector.

The other part of the district is the rural sector producing agricultural products, sold at a fixed price in international markets. Per-worker income in the agricultural sector is declining in total

[5] The migration literature is vast and reviewed in an earlier version of this paper (Henderson et al., 2014). Recent macro-level papers have studied climate's role in African domestic and international migration (e.g., Naudé (2010) and Marchiori et al. (2012)).

[6] The report defines heat extremes as 3-sigma events with respect to the 1951–1980 local distribution.

[7] 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 et al., 1994, Schlenker et al., 2006, Deschênes and Greenstone, 2007).

employment in the sector but increasing in moisture. Migration arbitrage between the urban and rural sectors equalizes real incomes across sectors and there is full employment in the district. Services market clearing closes the model. Total local production must equal total local demand, which incorporates income and price elasticities of demand for services.

We solve the model and consider comparative static effects of moisture on city population and total city income. The comparative statics expressions are complicated by the existence of the scale externalities in the urban sector, so we restrict to stable equilibria in migration between the urban and rural sectors. We consider two cases. In the first, the city has a manufacturing sector larger than a minimum size (defined precisely in Appendix B); in the second, it has no (or minimal) manufacturing. We find the following results, which are more precisely worded in the Appendix B.

Proposition 1. If the city has a tradable manufacturing sector (that is not too small relative to its local service sector), a decline in moisture will lead to an increase in urban population and total city income.

The intuition is simple. If moisture declines and manufacturing exists as an alternative to agriculture as a source of export-based employment, people leave the rural sector and move to the city to take up manufacturing employment. That expands city population and increases total city income, even though per person income in the district declines with the loss of agricultural productivity.

Proposition 2. If the city has a tiny or non-existent traded manufacturing sector, the effect of a decline in moisture on city population is ambiguous and tends to zero. In general, total city income declines.

With no manufacturing, there is no export-based employment other than agriculture, so no direct basis on which farmers move to the city. What happens to the city depends on the demand for urban non-traded services. With the decline in agricultural productivity, wages in the district decline, reducing demand for services, but that also means the cost and price of services declines, increasing the demand for services. As long as these two effects roughly offset each other, there is little or no effect on urban population and city total income will decline with the decline in real incomes in the district.

Whether a city has manufacturing is of course endogenous. In a static framework, with no mechanism to internalize scale externalities such as developers or governments setting up subsidized industrial parks (Desmet and Henderson, 2015), an absence of manufacturing implies that the wage the first worker in manufacturing would receive in the city is less than the equilibrium wage in the service sector. Manufacturing arises if either local (potential) productivity rises with, for example, enhanced education, or if the price of the manufactured good rises relative to the other goods, driven by changes in international prices or changes in the cost of transporting products between the local city and a port.[8] Since per-worker productivity with 1000 workers is higher than with one worker, with some coordinating force (e.g., industrial parks), lower prices or values of productivity can support the development of local industry. However, studying the development of local industry is beyond the scope of our work, if only because of a lack of data for most Sub-Saharan African countries. We ask whether climate affects urbanization and local incomes given existing industrial composition, but not whether it contributes to changes in industrial composition. In practice, as noted earlier, little structural transformation has occurred in most African countries.

[8] Atkin and Donaldson (2015) and Storeygard (2016) consider the transport cost story in Africa directly.

4. Data on urbanization, climate, and industrialization

In this section we discuss our measures of urbanization, moisture and extent of industrialization of districts, data we use in our analysis of the effect of climate on urbanization. We leave the description of the night lights data to Section 6.

4.1. Urbanization

Scarcity of demographic and economic data hampers empirical research on climate effects in Africa. Many countries carry out censuses only irregularly, and sample surveys such as the DHS are infrequent and provide little information before 1990.[9] While there are now a number of geographically detailed climate data sets that are increasingly used by economists (see Auffhammer et al. 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. We briefly show national level (non-) results below after our sub-national data analysis. We collected urban and rural population measures for sub-national regions (provinces and districts) from census reports. Systematic information about migration patterns is rarely available. We are thus unable to distinguish empirically between migration and net fertility and mortality differentials. We include countries with at least two available censuses with the relevant information for a complete or nearly complete set of sub-national units, where either district boundaries changed little or common units over time can be defined. The data were extracted mostly from hardcopy census publications obtained from the U.S. Census Bureau library, the U.S. Library of Congress, the LSE library, and the British Library.

The collected sample covers 32 countries but Namibia and Congo-Brazzaville are dropped because of problems with urban or district definitions.[10] We further limit the sample to intercensal periods of less than 20 years, so Liberia is omitted because its two available censuses were 34 years apart. We have information from 2 to 5 censuses between 1960 and 2010 for each of the 29 remaining countries (Fig. 3 and Appendix Table A1). For estimation purposes, Kenya is treated as two countries, before and after redistricting and urban redefinition of the 1990s. Each country is divided into a number of sub-national units we call districts. The 369 districts are shown in Fig. 3. As noted in Table 1 the districts are large, on average 41,000 sq. km., with considerable variability across countries. The most notable omission is Nigeria, Africa's most populous country, because of concerns over the quality of census figures (see, e.g., Okafor et al., 2007).[11] Other Sub-Saharan African countries are missing because either they had no censuses with needed information or because we were unable to obtain the printed volumes. We exclude South Africa because province maps

[9] The World Fertility Surveys of the late 1970s and early 1980s (DHS precursors) have limited country coverage and surveyed only women.

[10] For Namibia, the problem is changing district boundaries and urban definitions. For Congo most districts were originally drawn to be either wholly urban or wholly rural, making within-district analysis impossible. Three censuses of Botswana are similarly removed because more than half of units at the highest level of aggregation contain no urban population.

[11] Because Nigeria is so large, we devoted considerable effort to exploring its data. The two Nigerian censuses since 1963, in 2006 and 1991 are widely thought to be inaccurate, because provinces and cities have incentives to inflate their populations to increase their share of oil rents. Moriconi-Ebrard et al. (2008, 2016) devote enormous effort to estimate the population of individual cities by decade, and give many examples of substantial deficiencies in the census data. In order to produce a complete dataset, ultimately they rely on the 2006 census, and extrapolate backwards using the population growth rates of local government areas (which do not match their city definitions). A further source of information on why Nigerian censuses are problematic is https://africacheck.org/factsheets/factsheet-nigerias-population-figures/.

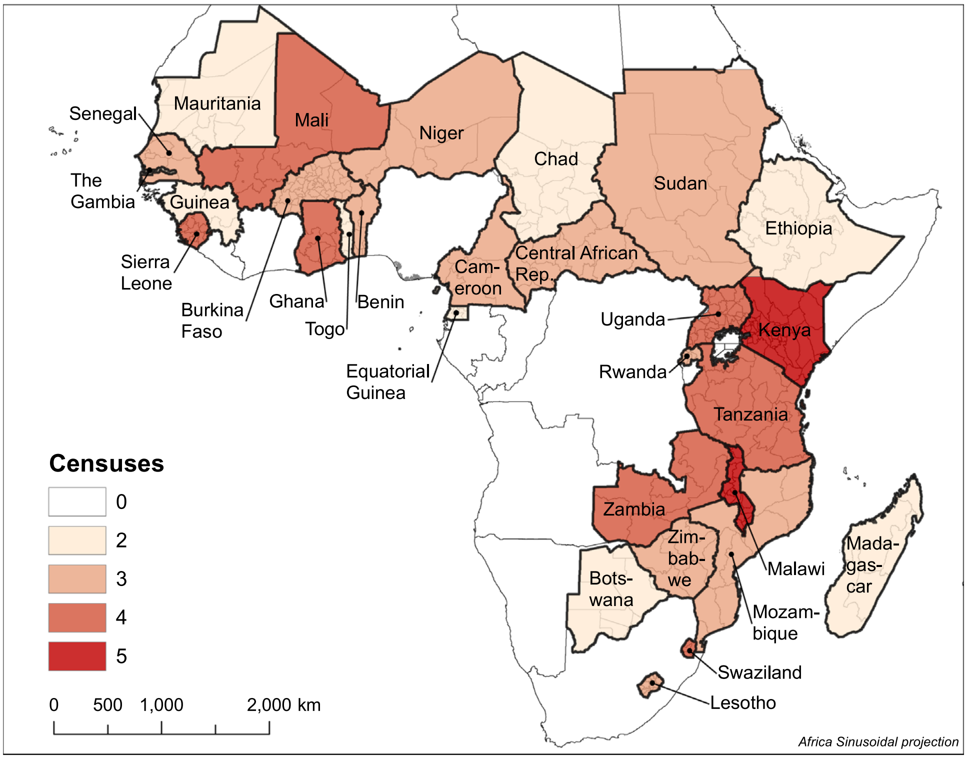

Fig. 3. Census data sample.

Table 1
Summary statistics.

	Mean	SD	Min	Max
Panel A: Urban share growth (N = 717)				
Annualized moisture growth	−0.00439	0.0139	−0.0469	0.0326
District moisture 1950–69	0.983	0.448	0.0306	2.291
Annualized growth in urban share	0.0310	0.0418	−0.0822	0.191
Initial share urban	0.139	0.209	0	1
ln(distance to coast)	5.981	1.203	−0.0908	7.477
Land area, km^2	40,877	78,686	72.64	623,518
9 – #modern industries	8.505	1.474	0	9
14 – #all industries	13.09	2.415	0	14
1(base moisture > 1)	0.484	0.500	0	1
Panel B: lights growth (N = 19865, 18527 differences)				
ln(rain) 30 km	0.710	0.687	−8.678	2.497
1(%GDP in agriculture > 30%)	0.738	0.440	0	1
Δln(rain(t))	0.00975	0.333	−5.086	5.743
Δln(lights)	0.0651	0.682	−6.792	6.970
10 – #modern industries	9.828	0.905	0	10
14 – #all industries	13.68	1.453	0	14
1(national conflict)	0.249	0.432	0	1
1(inside conflict)	0.0218	0.146	0	1
1(outside conflict)	0.0496	0.217	0	1

were redrawn post-Apartheid, and Apartheid-era migration restrictions make it a special case.

4.2. Climate

With few exceptions, most studies of climate impacts on agriculture focus exclusively on precipitation. However, plant growth is also a function of temperature, decreasing in the relevant range, for two reasons. First, water evaporates from the soil more quickly as opposed to reaching roots. Second, photosynthesis increases more slowly with temperature than transpiration. Thus, dividing precipitation by potential evapotranspiration (PET), which is the appropriate non-linear function of temperature, increasing in the relevant range, creates a better measure of climatic agricultural potential. Although this measure is often called an aridity index and used to define aridity zones (UNEP, 1992), we call it a moisture index, because larger values indicate relatively greater water availability, with values above one indicating more moisture than would be evaporated given prevailing temperature (Vose, 2014; Banda, 1990). Precipitation and temperature data are from the University of Delaware gridded climate data set (Willmott and Matsuura, 2012). We estimate monthly PET from 1950 to 2010 using the Thornthwaite (1948) method based on temperature, number of days per month and average monthly day length, and subsequently aggregate monthly values to obtain annual totals (see, e.g., Willmott et al. (1985) for details).[12] As a robustness check, we also enter rainfall and temperature separately. The results show that while precipitation alone has an effect similar to moisture's, temperature also has a strong effect, which moisture captures.

Fig. 4 shows average annual country-level moisture trends for the countries in our sample, indicating the long term downward

[12] More specifically, potential evapotranspiration (PET) for month i is calculated as:

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

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, $\alpha = \left(6.75\times10^{-7}\right)I^3 - \left(7.71\times10^{-5}\right)I^2 + \left(1.792\times10^{-2}\right)I + 0.49$, and the heat index $I = \sum_{i=1}^{12}\left(\frac{T_i}{5}\right)^{1.514}$. The Penman method provides a more accurate estimate of PET, but requires data on atmospheric conditions that are not available consistently for the area and time period of this study.

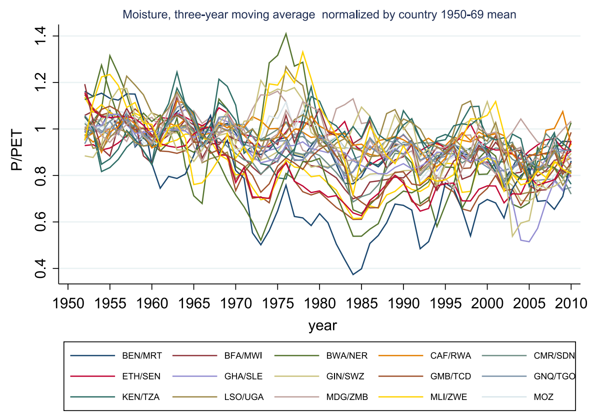

Fig. 4. Variability in climate change in Africa.

trend over the last 60 years, consistent with Fig. 2. It also shows the high inter-annual variability of moisture in these countries, even with three-year smoothing. The climate data sets have a spatial resolution of 0.5 degrees, which corresponds to about 3000 km^2 at the equator. To generate district level climate indicators, we average grid cell values that overlap with the corresponding sub-national unit, weighting by area in the case of cells that cross district boundaries.[13]

4.3. *Extent of industrialization*

Our model suggests that places with export industries will respond differently than other districts. Sub-national data on industrialization from African censuses is scarce; even data on the share of manufacturing in GDP at the national level is scarce before 1985. For an analysis of urbanization based on outcomes from 1960 onwards, we need a base from the beginning of that period. Fortunately, as noted by Moradi (2005), the *Oxford Regional Economic Atlas, Africa* (Ady, 1965) maps all industries by type and city location in Africa, based on an in-depth analysis from a variety of sources from the late 1950s and early 1960s. We integrated these maps with our census data to locate all places with any of 26 different manufacturing industries. We refer to 16 of these as "modern": iron/steel, electrical equipment, general engineering equipment, cement, other building materials, rubber, petroleum refining, printing, general chemicals, paints/varnish, glass/pottery, footwear, and four types of textiles. Fig. 5a shows the count of modern industries found in each of our districts, where the maximum is 9 of the 16. Only 16% of our districts had any of these industries, suggesting that there may be limited scope for the induced industrialization channel in our model. Fig. 5b maps all industries from Ady (1965), combining the 16 modern industries with the remaining 10 agricultural processing industries: brewing, wine/spirits, tanning, canning, and the processing/milling/refining of sugar, oil, cotton, grain, tobacco and timber. Twenty-three percent of sample districts have an industry in this wider set, with at most 14 different industries in a single district. However, despite the small fraction of districts with these industries, they are well-represented across countries: 18 sample countries have a modern industry and 19 have an industry in the wider set.

In our empirical work, we use these counts of modern industries and all industries as measures of 1960s extent of industrial activity in a district or city. The modern measure has the advantage that it excludes food processing, which uses agricultural inputs whose availability and price could be affected by climate. However, the number of cities with a modern industry is low in some subsamples, and ultimately the role of these historical formal sector industry counts is to serve as a proxy capturing industrial capacity or propensity to have export industries of all types. Thus we use the all industry count for most robustness checks, especially when both sets of results are essentially the same or when the count of cities with modern industries in a specific sub-sample is low.

Although the analysis of growth in night lights in Section 6 starts 30 years after these industry data, we find that the maps are still a good proxy. Specifically, in 111 districts of the 7 sample countries with IPUMS data on manufacturing as a fraction of the urban labor force from censuses carried out between 2000 and 2009, our modern and all industry counts are correlated with this labor force measure at 0.34 and 0.40, respectively, net of country fixed effects.[14] As an alternative, we also experiment with a more recent country-level measure of the extent of industry to proxy for whether a city is likely to export manufactures.

5. Empirical analysis of the effect of climate on urbanization

5.1. *Specifications*

We estimate the effect of growth in moisture on growth in urbanization for a panel of districts that is unbalanced because different countries conduct censuses in different years. Growth rates are annualized to account for the different lengths of these intercensal periods. The base specification is

$$u_{ijt}=\beta_0 w_{ijt}+\beta_1 X'_{ij} + \beta_2 X'_{ij}\, w_{ijt}+\alpha_{jt}+\varepsilon_{ijt} \qquad (1)$$

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 $t - L_{jt}$ to t and L_{jt} is the number of years between year t and the prior census;

$w_{ijt}=\left[\ln W_{ijt}-\ln W_{ij,t-L_{jt}}\right]/L_{jt}$, and W_{ijt} is average moisture from $t-2$ to t (inclusive);

X_{ij} are time-invariant controls;

α_{jt} is a country-year fixed effect controlling for time-varying national conditions; and

ε_{ijt} is an error term clustered by district.

In (1), growth in urbanization is a function of growth in moisture. The growth specification removes the effect of time-invariant district characteristics (distance to other locations such as the coast, soil quality and the like) on urbanization *levels*. However these factors (X_{ij}) could also affect the impact of climate changes on urban share *growth rates*. We control for country-year fixed effects to account for national time-varying conditions driving urbanization overall in a country. This helps control for variation across countries in the definition of urban areas, a significant problem in cross-country urban analysis. What we are doing is demanding on the data—identification of climate effects on urbanization must come from within-country differences across districts in annualized growth rates of moisture.

We smooth moisture levels over three years, on the assumption that potentially permanent decisions are more likely to be based on average recent experience rather than one good or bad year. As an example, the annualized rate of change in urban share between censuses in 1965 and 1980 is estimated as a function of the annualized rate of change in moisture between the average for 1963, 1964 and 1965 and the average for 1978, 1979 and 1980. We

[13] In practice, we use the number of 0.1-degree sub-cells as a weight.

[14] Minnesota Population Center. Integrated Public Use Microdata Series, International: Version 6.3 [Machine-readable database]. Minneapolis: University of Minnesota, 2014.

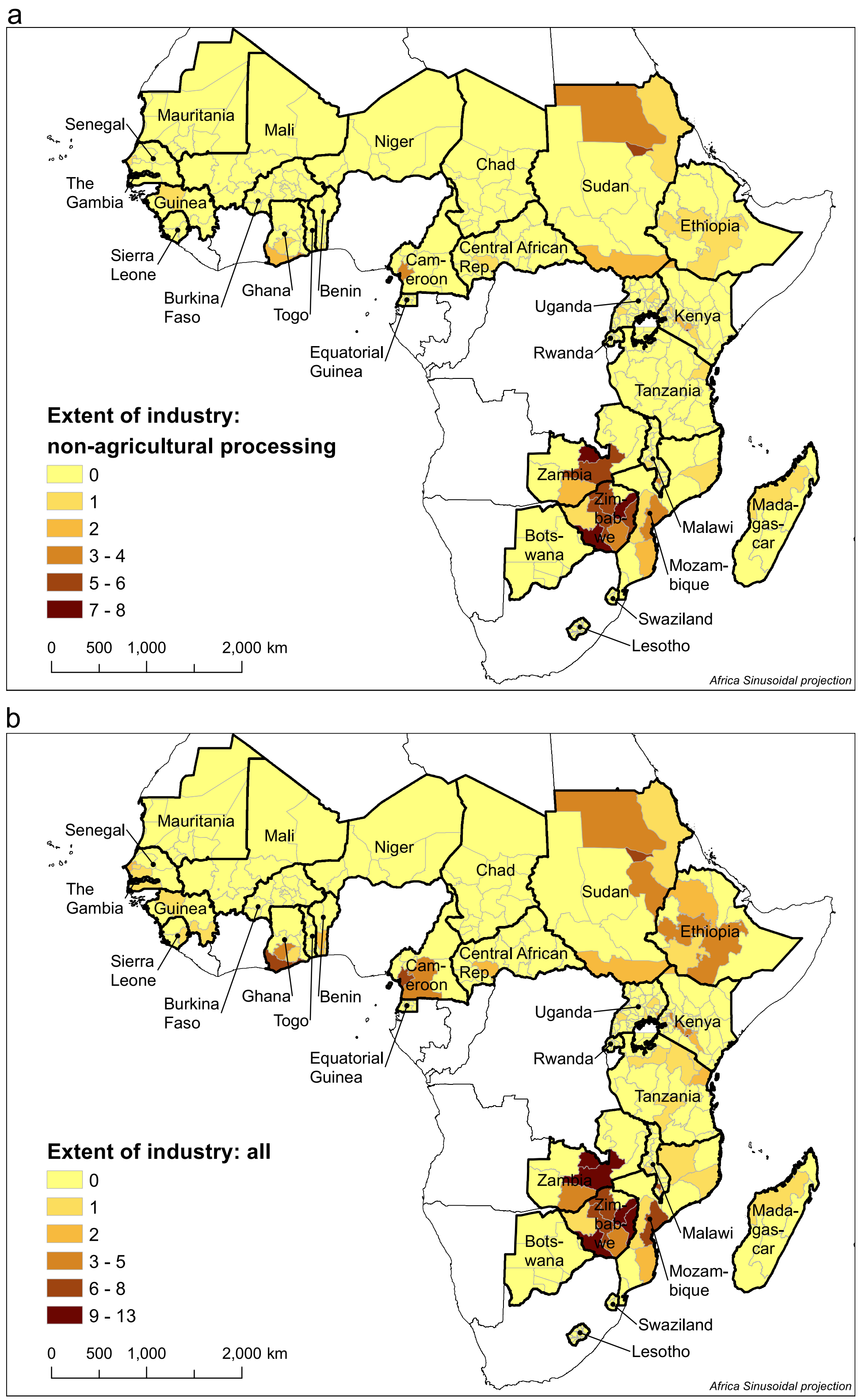

Fig. 5. a. Extent of modern industries, circa 1960. b. Extent of all industries, circa 1960.

further explore the choice of smoothing period and robustness of results to alternatives in Section 5.3.2.

Our theoretical model suggests two important forms of heterogeneity, based on industrial capacity and aridity. We measure these using industrial capacity from Ady (1965), as described in Section 4.3, and district-level average moisture for 1950–69. In Section 5.3.4, we briefly discuss heterogeneity based on additional factors such as soil quality and measures of climate variability.

Table 1 Panel A presents summary statistics on the estimating variables. The average annualized growth rate of moisture is

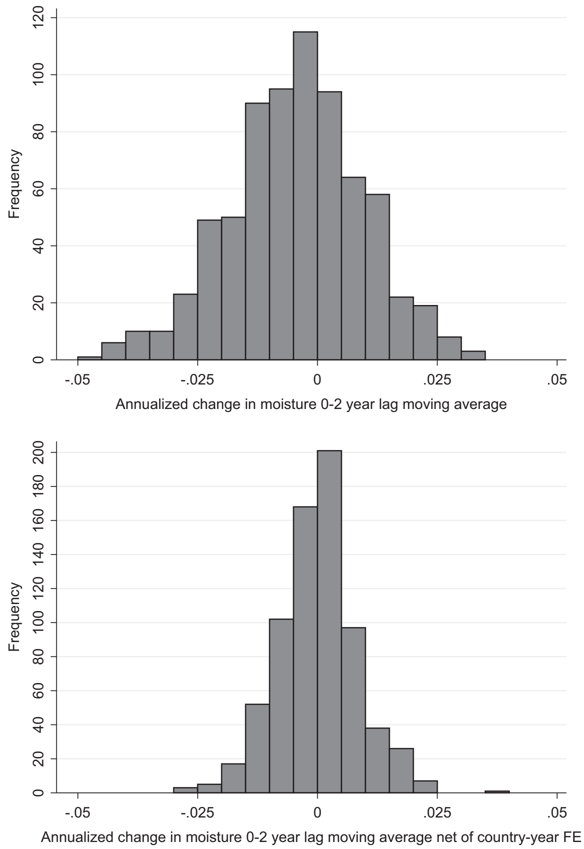

Fig. 6. Distribution of Change in Moisture. a. Raw data. b. Factoring out country-year fixed effects.

negative, consistent with Fig. 2, and the average growth rate in the urban share is positive. We are concerned that outliers in these variables could reflect measurement problems. For example, an extremely high urban share growth rate could be due to a poorly measured low base. An extremely high or low moisture growth rate could reflect intercensal changes in the density of weather stations. We thus trim observations from the top and bottom of the distribution of growth rates in both urban share and in moisture. In our main specifications, we drop the highest and lowest 6 growth rates of each variable, or 24 observations out of 741, which is about 3.2% of the total sample. In Section 5.3.2 we explore the robustness of results to deviations from this choice.

5.2. Identification

Our chief identification concerns are insufficient within-country variation and omitted variables. In Fig. 6a, the growth in moisture variable has more density to the left of zero, consistent with overall drying, and a large spread of positive and negative values. However, Fig. 6b shows that spread does shrink somewhat after factoring out country-year fixed effects. The extent of industrialization measures lose little such variation. The standard deviation of the modern industry measure decreases from 1.47 to 1.27 net of country fixed effects, while the analogous figures for the broad industry measure are 2.42 and 2.12. With respect to omitted variables, since changes in climatic conditions are exogenous and in principle randomized by nature across districts, estimates of reduced form (or net) effects may appear to be unbiased. We have differenced out time-invariant factors affecting urbanization levels. However, unobservables affecting growth in urbanization could be correlated with climate change within our

Table 2
Effect of moisture on urbanization: heterogeneity by industrialization.

	(1)	(2)	(3)
Δmoisture	−0.0761	−1.064***	−1.164***
	(0.180)	(0.360)	(0.354)
Δmoisture × (9 – #modern industries)		0.116***	
		(0.0414)	
Δmoisture × (14 – #all industries)			0.0824***
			(0.0263)
(9 – #modern industries)/1000		−0.51	
		(1.22)	
(14 – #all industries)/1000			0.131
			(0.727)
Initial share urban/1000	−48.9***	−55.0***	−52.0***
	(5.53)	(8.79)	(8.15)
ln(distance to coast)/1000	1.43	1.55	1.47
	(1.89)	(1.87)	(1.89)

Notes: Each column is a separate regression with 717 observations for 359 districts. The dependent variable is growth in the urbanization rate. 9 and 14 are the maximum number of modern and total industries, respectively, in any district. Robust standard errors, clustered by district, are in parentheses. All specifications include country × year fixed effects. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

limited sample. In fact none of the covariates we consider have significant correlation with the growth in moisture variable, except for log distance to the coast.[15] In particular, indicators of initial industrialization and moisture status are not correlated with subsequent moisture changes. In that sense, there is balance in the data when we examine heterogeneity based on whether or not an area is initially industrialized and/or moist. We add two main controls: initial urbanization and log distance to the coast, both representing a variety of factors. For example, initial urbanization is correlated with growth in urbanization (i.e. mean reversion) and modestly but insignificantly with growth in moisture. Controlling for initial urbanization may raise concerns because, for the first growth incident in each district, it is used to calculate the growth in urban share, the dependent variable. Below in Section 5.3.2, we show robustness to dropping these controls.

5.3. Main results

Tables 2–5 report on several specifications of the effect of moisture growth on urbanization. Tables 2–4 report our district-level specifications relying on within-country variation. Table 2, after showing the overall average effect, explores the effect of allowing for heterogeneity in the likelihood of having industry. Table 3 (along with Table A2) considers the robustness of these results, including to different climate measures. Table 4 explores effects allowing for heterogeneity in initial moisture level and combines the two sources of heterogeneity. Table 5 reports country-level results, for comparison with the literature.

5.3.1. District level urbanization, with heterogeneity based on likelihood of industrialization

In Table 2, moisture effects are defined by within-country-period differences in districts' urbanization growth in response to differences in district moisture growth rates. In column 1, the effect of moisture growth alone on urbanization is insignificant in the sample of districts, suggesting that there is no effect on average. Significant and distinct effects only arise when heterogeneity is introduced. The rest of the table explores heterogeneity based on the

[15] In addition to variables we use in analysis, this includes indicators for French and British colonial ties.

Table 3
Robustness of moisture effects.

	(1)	(2)	(3)	(4)	(5)
Δmoisture	−1.155** (0.517)	−0.359 (0.572)	−1.165** (0.582)		
Δmoisture × (14 − #all industries)	0.0826*** (0.0286)		0.0664 (0.0481)		
neighbors' Δmoisture			0.250 (0.685)		
neighbor's Δmoisture × (14 − own #all industries)			0.0154 (0.0515)		
Δprecipitation				−1.051*** (0.378)	−0.457 (0.438)
Δtemperature					8.784** (3.786)
Δprecipitation × (14 − #all industries)				0.0677** (0.0284)	0.0201 (0.0338)
Δtemperature × (14 − #all industries)					−0.934*** (0.279)
(14 − #all industries)/1000	0.133 (0.729)	−0.210 (0.745)	0.200 (0.718)	−0.022 (0.738)	0.746 (0.729)
Initial share urban/1000	−52.0*** (8.16)	−50.3*** (7.82)	−52.1*** (8.33)	−51.3*** (8.09)	−52.9*** (7.83)
ln(distance to coast)/1000	1.45 (1.89)	1.91 (1.82)	0.862 (1.87)	1.63 (1.90)	1.71 (1.94)
Δmoisture × ln(dist. to coast)/1000	−1.83 (94.1)	47.6 (96.7)			

Notes: Each column is a separate regression with 717 observations for 359 districts. The dependent variable is growth in the urbanization rate. 14 is the maximum number of industries in any district. Robust standard errors, clustered by district, are in parentheses. All specifications include country × year fixed effects. *$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

Table 4
Moisture change and urbanization: heterogeneity by industry and aridity.

	(1)	(2)	(3)
Δmoisture	−0.385** (0.180)	−1.385*** (0.414)	−1.493*** (0.417)
Δmoisture × 1(base moisture > 1)	0.783*** (0.300)	0.638 (0.712)	0.641 (0.731)
Δmoisture × (9 − #modern industries)		0.117** (0.0482)	
Δmoisture × (14 − #all industries)			0.0833*** (0.0311)
Δmoisture × (9 − #modern industries) × 1(base moisture > 1)		0.0191 (0.0868)	
Δmoisture × (14 − #all industries) × 1(base moisture > 1)			0.0124 (0.0584)
F-test that base moisture and its interactions are jointly zero		2.44	2.54
P-value		0.0249	0.0202

Notes: Each column is a separate regression with 717 observations for 359 districts. The dependent variable is growth in the urbanization rate. 8 and 13 are the maximum number of modern and total industries, respectively, in any district. Robust standard errors, clustered by district, are in parentheses. All specifications include country × year fixed effects and controls for initial urbanization and ln(distance to the coast), alone and interacted with the base moisture variable. Columns 2 and 3 additionally include the relevant industry variable alone and interacted with the base moisture variable. *$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

likelihood of having export manufacturing, as opposed to only agriculture and local services. In column 2 we use a proxy for the absence of industry based on the number of modern (non-agricultural processing) industries present. The measure has a value of zero if a district has the maximal count (9) of these industries and then rises as the number of industries declines, to a maximum of 9 in districts with no such industries (84% of the sample). The base moisture coefficient thus applies directly to the most industrial districts. This measure is analogous to an inverse of the continuous manufacturing to services ratio in our model. Consistent with the model, effects fall with reduced manufacturing. Column 3 applies the analogous measure for a broader class of industries that includes agricultural processing. The maximum number of industries in this class observed in a district is 14 (of 26). 77% of districts had no industry in the early 1960s.

Based on either modern or all industries, point estimates in columns 2 and 3 suggest a very large effect for the most likely industrialized districts of −1.06 and −1.16. A one standard deviation decrease in the growth rate of moisture increases the growth rate of share urban by about 0.015, where that growth rate

Table 5
Effect of moisture change on national urbanization and primacy.

	(1) Δurban	(2) Δurban	(3) Δurban	(4) Δurban	(5) Δprimacy
Δmoisture	0.210	−0.0296			−0.0628
	(0.168)	(0.216)			(0.139)
Δmoisture × (72 − #all city × industries)/1000		4.19			
		(4.32)			
Δprecipitation			0.169	−0.113	
			(0.183)	(0.303)	
Δprecipitation × (72 − #all city × industries)/1000				4.70	
				(5.74)	
(72 − #all city × industries)/1000		0.183		0.180	
		(0.120)		(0.120)	
(25 − #all city × industries (primate))/1000					0.23
					(0.359)
Δmoisture × (25 − #all city × industries (primate))/1000					−12.4
					(25.0)
(47 − #all city × industries (non-primate))/1000					0.0864
					(0.201)
Δmoisture × (47 − #all city × industries (non-primate))/1000					0.0154
					(12.3)

Notes: The maximum number of city × industries is 72 (total), with 25 for the primate and 47 for the non-primates. Robust standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. There are 60 observations.

has a mean of 0.03. In these columns, as the extent of industry decreases, the effect diminishes at rates of 0.12 and 0.082, respectively, per industry lost. Thus for districts with no industry (over 75% of our sample), the net marginal effect of moisture growth is about zero in both columns. These results are consistent with the theory we presented: there is a strong negative effect of moisture growth on urbanization in industrialized districts but little or no effect in agricultural ones.

In Fig. 7, we report results using a more flexible form of our industry variable. Fig. 7a does this for 5 bins of modern industries and Fig. 7b for 7 bins of all industries. The patterns are clear. Relative to no effect at 0 industries and little or none at 1–2, as the number of industries increases, increases in moisture lead to greater and greater reductions in growth rates of urbanization. The non-parametric results suggest our specification in Table 2 is a very good approximation.

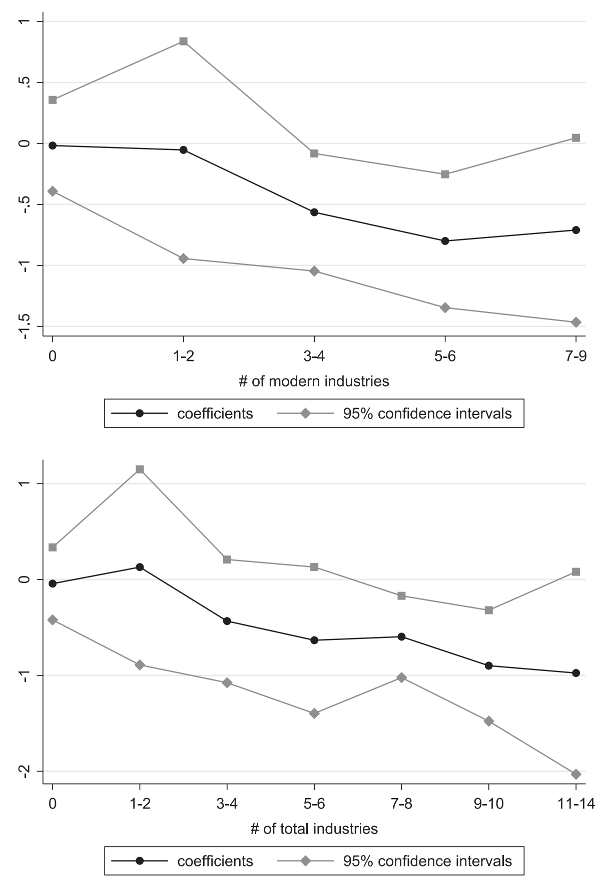

Fig. 7. Non-parametric representation of effects of moisture under different degrees of industrialization. a. Modern industries. b. All industries.

5.3.2. Robustness

Table 3 and Appendix Table A2 explore robustness of these results to the choice of specifications and variable definitions, using the all industry count specification from Table 2 column 3. Results for modern industry follow the exact same patterns. In Table 3 columns 1 and 2, we explore whether our all industry measure is capturing general effects of distance to the coast, although the two measures are not strongly correlated in our data. In the two columns, we add log distance to the coast interacted with the change in moisture, with and without the all industry measure and its moisture change interaction. In both cases the distance to coast interaction is insignificant. The base effects of change in moisture and its interaction with the industry measure in column 1 of Table 3 are very similar to results in column 3 of Table 2. We also note that the industry measure could proxy for aspects of a district's size. However, if we regress the measure on log district area and population and use the resulting residuals in place of the raw industry measure, our results are essentially the same.[16]

While, as noted above, most migration is local, inter-district migration does occur. Column 3 of Table 3 includes the average change in moisture of a district's neighbors, alone and interacted with the all industry measure. If a neighboring district's moisture declines, its rural population might migrate to work in the own-district's cities, rendering the new interaction term negative. However the covariate and its interaction with the degree of

[16] Specifically, the marginal effect of moisture change for the most industrial region is −1.008 (s.e. 0.337) and the interaction term coefficient is 0.078 (s.e. 0.029).

non-industrialization are both small and insignificant. Since a district's climate patterns are correlated with those of its neighbors, standard errors on the two own-district terms of interest rise, but their point estimates are similar to those in Table 2. Neighbors could also affect the error term. Appendix Table A3a reports the Table 2 specifications with Conley (1999) standard errors. They are very similar to those in Table 2, with no systematic pattern; some are modestly higher and some modestly lower.

Column 4 of Table 3 explores the effect of using precipitation instead of moisture. Results are almost the same as in Table 2, which is reassuring. In Section 6 below, we use precipitation exclusively, because we cannot calculate moisture at such a fine spatial scale without relying excessively on interpolation. Column 5 shows however that in a horse race of temperature versus rainfall, temperature is the dominant variable. The problem of course is that changes in the two are correlated (coefficient = −0.34) and climatologists see temperature entering in a non-linear fashion. For these reasons we prefer the moisture measure when available. Finally, we note that no single country is driving the results. We run DFBETA tests, iteratively dropping each country from the Table 2, column 3 specification results in a main coefficient range −1.417 to −0.957 (t-statistic range −4.02 to −2.67), and an industry interaction coefficient range of 0.0673 to 0 .0907 (t-statistic range 2.48–3.29).

The results we have presented all trim the sample, include controls, and smooth climate growth rates in the same way. Appendix Table A2 explores robustness of results to the choices we made, based for illustration on the Table 2, column 3 specification (results for column 2 mirror these). Our main specifications smooth moisture over 3 years (0 to 2 before each census) before calculating growth rates. Compared to the base in Appendix Table A2 Panel A column 1, in columns 2 and 3, smoothing over 4 or 5 periods provides similar results. Smoothing over just 2 (column 4) leaves more noise and gives distinctly weaker results. Next, we report the effects of dropping controls for initial urbanization and log distance to the coast in columns 5–7. The magnitudes of significant coefficients are only modestly affected. With respect to trimming, our choice of sample is conservative. With no trimming, both the base effect and the rate of diminution are considerably enhanced (Panel B, column 2). Very modest trimming initially gives smaller magnitudes than in Table 2, but then coefficients stabilize at the point we report where we trim 6 from each of the top and bottom values of growth in moisture and growth in urban share, which is about 3.2% of the sample overall. Coefficients are little affected by trimming further up to, for example, 8.6% of the sample in column 6. We pick the largest sample where coefficients have stabilized.

It is also worth noting that while initial urbanization is correlated with the extent of industry in a district, it is not a good proxy for industrial status or extent. In Table A2, Panel B column 7 shows the results for a regression where the lack of industry in a district is measured by a district not being in the top quintile of districts by initial urbanization. Results are small and insignificant (as they are when moisture growth is interacted with a continuous measure of initial non-urbanization).

5.3.3. *Heterogeneity based on initial aridity and industry*

Table 4 examines the effect of moisture growth allowing for heterogeneity in both initial aridity and industry. If there are decreasing marginal returns to rainfall, one might think that any moisture effects would be less in non-arid regions, where agriculture typically has sufficient rainfall. Column 1 first shows the effect of just allowing for heterogeneity based on whether a district is moist (moisture index in excess of 1.0) on average in 1950–1969, or not. In arid areas, moisture increases reduce urbanization while for moist districts the net effect is actually positive, though not significant.

Columns 2 and 3 of Table 4 combine the two sources of heterogeneity, to distinguish industrialization effects in arid versus moist areas, using the two different measures of industry. Both include appropriate interactions of all covariates with the moisture indicator variable to distinguish arid from moist places, but only the key coefficients are shown. In the top row of each column, we show the effect of moisture growth in arid places that are most industrialized. Heterogeneity is again distinct across levels of industry likelihood, but not between arid and moist places. However, the joint effect of the moisture indicator is significant in both columns, and distinguishing arid from moist districts shows larger climate change effects in the most industrialized districts that are arid, compared to those effects for all districts combined in Table 2. For example, in column 3, the baseline effect is −1.49, so that in the most industrialized areas in an arid district, a one standard deviation increase in moisture reduces urbanization by 0.021, or 67% of the mean growth rate in share urban. However, we note results can be sensitive to definition of the arid zone. For example one might ask if the Sahel region, with its higher concentration of animal husbandry, might be different. If we rerun Table 4 column 3 replacing the moisture dummy with a Sahel one, base coefficients are similar to those in column 3 of Table 2, and the Sahel ones (and standard errors) are respectively 0.771 (0.865) for moisture and −0.0656 (0.0524) for the interaction, which hints weakly at dampened effects in the Sahel relative to non-Sahel places. Given the size of our sample, we have limited ability to cut it into many categories.

5.3.4. *Other dimensions of heterogeneity*

The effect of moisture on urbanization may differ along many other dimensions. We considered six possibilities, fully interacting each with the Table 2 column 3 specification.[17] The results were weak in all cases, providing no evidence of significant heterogeneity in other dimensions. For the record, we tried three measures of agricultural productivity that might influence the effect of moisture changes: soil water capacity and total soil suitability from Ramankutty et al. (2002), and evidence of modern irrigation infrastructure/potential from Siebert et al. (2007).[18] For the last we expected nothing since irrigation potential is so limited in our sample (4%). The other three are measures of weather variability within and across years, which might make farmers more or less vulnerable to change. One is a Gini of rainfall across months within the year to measure rainfall concentration within the year, using baseline 1950–69 data. The other two are the standard error of the linear prediction of rainfall between censuses, to measure noise in the growth in climate variable, and the intercensal change in the standard deviation of rainfall in the 10 (or 17) years before a census.[19]

5.3.5. *Country-level urbanization and primacy*

Table 5 reports cross-country results, using the same sample of censuses described above. In columns 1–4, the dependent variable is the annualized growth rate of the national urban population share. In columns 1 and 2 the focus is on the key independent variables we use above, measured here at the national level. Column 1 shows the overall effect of growth in

[17] Each new variable is interacted with Δmoisture, Δmoisture $\times$ (14-# all industries) and (14 -# all industries).

[18] 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.

[19] Based on the annualized growth rate, w_{ijt}, from Eq. (1), we can formulate the predicted value for moisture in any year between census intervals as $\hat{W}_{ijt} = W_{ijt-L_{jt}} e^{w_{ijt}}$. From that we form the standard error of prediction: $SEP_{ijt} = \sqrt{\sum_{s=t-L_{jt}}^{t} (\hat{W}_{ijs} - W_{ijs})^2 / (L_{jt} - 2)}$.

moisture and column 2 explores the heterogeneity with respect to industrialization. In column 2, the base moisture coefficient is for a country with the maximal recorded industry (the maximum count in different industries in different districts). For a country with no industry the net effect is the coefficient on growth of moisture plus 72 times the coefficient on the interaction term. We expect the negative effect of moisture growth on urbanization in the most industrialized countries to be reduced as the degree of industrialization declines. While that is the pattern in column 2, all covariates are small and insignificant. Replacing the count of district-industries with the count of unique industries in the country, or adding country time trends, does not change this. In columns 3–4 we replace the moisture variable with annualized growth in precipitation, as is used in much of the literature, but again there is no effect. While we find nothing of significance at the national level in the many specifications we tried, our results are not directly comparable to those in Barrios et al. (2006). They use populations estimated by the UN at 5 year intervals for 1960–1990 for a larger and on average earlier sample. Similarly, Brückner (2012) uses a larger sample at 1-year intervals.

In column 5 we consider growth of primacy: the share of the largest city in national population. While our model and the specification below focus on within-district movements of population, in a continent where primate cities generally dominate the urban landscape, it may be that a common response to bad climate shocks is to move to the primate city rather than locally. We define the primate city broadly, to approximate the extent of the primate labor market, further including the urban areas of districts with substantial areas of lights at night contiguous to the officially defined primate city. Moisture growth in the rest of the country on its own has no impact on primacy growth (results not shown). In column 5, as might be expected, in the most industrialized countries for the most industrialized primate cities, moisture growth in the rest of the country deters growth of the primate, but the effects are small and insignificant. The interaction terms are similarly insignificant. We found no pattern of stable significant results on primacy.

6. Climate change and city income

Having shown evidence of the population effects predicted by our model, we turn to effects on city total income. Our theory indicates that if the local town performs an exportable activity, reduced moisture unambiguously raises city income. However if the local town exists solely to provide farmers with goods and services that are not tradable outside the district, then the fortunes of the urban and rural sector are tied. Decreased moisture is then likely to decrease local city income. In one sense, looking at how cities fare is a check on the implication that migration is driving the urbanization results. Moisture declines adversely affect per person incomes in the district, so total income in the city can only rise if there is in-migration. However, we are now considering a very different temporal and spatial scale. Rather than looking at urbanization over 10–15 years as a function of climate change over those years, given the nature of our income-related data, we will be looking at the impact of annual climate fluctuations on annual city incomes and implied (possibly short-term) migration. Spatially, we will be looking at cities and rainfall within 30 km of them, as opposed to districts that average 41,000 square km.

Data on income or city product are not consistently available for African cities, so we use an indirect measure. Following the approach in Henderson et al. (2011, 2012), we test whether the intensity of nighttime light emitted by a city is affected by the amount of rainfall within 30 km of each city in the current or prior year (see Fig. 8). The nighttime lights data also allow us to include countries like Nigeria with weak population data. They come from the U.S. Defense Meteorological Satellite Program (DMSP), a satellite system originally designed for weather observation, that captures visible light emitted between about 8:30 p.m. and 10 p.m. We use annual average data from 1992 to 2008 for 30 arc-second grid cells (0.86 km^2 at the equator). The data product typically used for socioeconomic analysis contains only stable lights after temporary light sources such as forest or savannah fires have been removed (e.g., Elvidge et al., 1997). An infrared sensor detects clouds so that only cloud-free nights are incorporated into the annual averages. Thus clouds and rainfall have no direct effect on the detection of lights. We further remove gas flares based on Elvidge et al. (2009). Light intensity for each pixel is expressed as a “digital number” (DN) linearly scaled between 0 and 63.

In Henderson et al. (2012), changes in lights are used to reflect total income changes. In the work underlying that paper, considerable effort was made to decompose such changes into income per capita versus population changes at the regional level in specific countries, since knowing about how income per capita changes is also of interest. Results on decompositions were not robust. Here while we would also like to know the impact on urban per capita as well as total incomes, an additional problem is that we do now have annual population data for cities, or even multiple independent population estimates falling with the time period of the lights for the large majority of countries.

6.1. Specification

Our analysis includes 1158 cities and towns in 42 countries (all of mainland sub-Saharan Africa except Somalia, plus Madagascar). Following Storeygard (2016), we define cities as contiguous lit areas in the DMSP data set for which a recent population estimate is available from a comprehensive census-based database.[20] More specifically, we overlay lit areas for all years and find the outer envelope of lights as pictured in Fig. 8. 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 this outer envelope (maximum extent) of the city light footprint. We exclude lit areas directly adjacent to an international border to reduce measurement error associated with overglow of lights across the border. We use rainfall measures from the Africa Rainfall Climatology Version 2 (Novella and Thiaw, 2012), which combines weather station data with satellite information, resulting in a shorter time series but a finer spatial resolution (0.1 degree) than Willmott and Matsuura (2012). We use rainfall rather than moisture in this section because we are unaware of temperature measures at such fine resolution that do not heavily rely on interpolation of sparse data. Each city's hinterland annual average rainfall is calculated as an average of grid-cell values within 30 km of the ever-lit area. To define arid areas, we calculate average near-city rainfall between 1983 (the first year in the data) and 1991, and split at the sample median (recalling that in Section 5 the moisture cut-off divided the sample almost evenly). Summary statistics are in Table 1, Panel B.

Our specification is

$$\ln(light_{it}) = \sum_{j=0}^{k} \beta_j \ \ln\ (rain_{i,t-j}) + \sum_{j=0}^{k} \gamma_j X_i' \ \ln(rain_{i,t-j}) + \phi_i + \lambda_t + \alpha_i t + \varepsilon_{it} \quad (2)$$

[20] http://www.citypopulation.de.

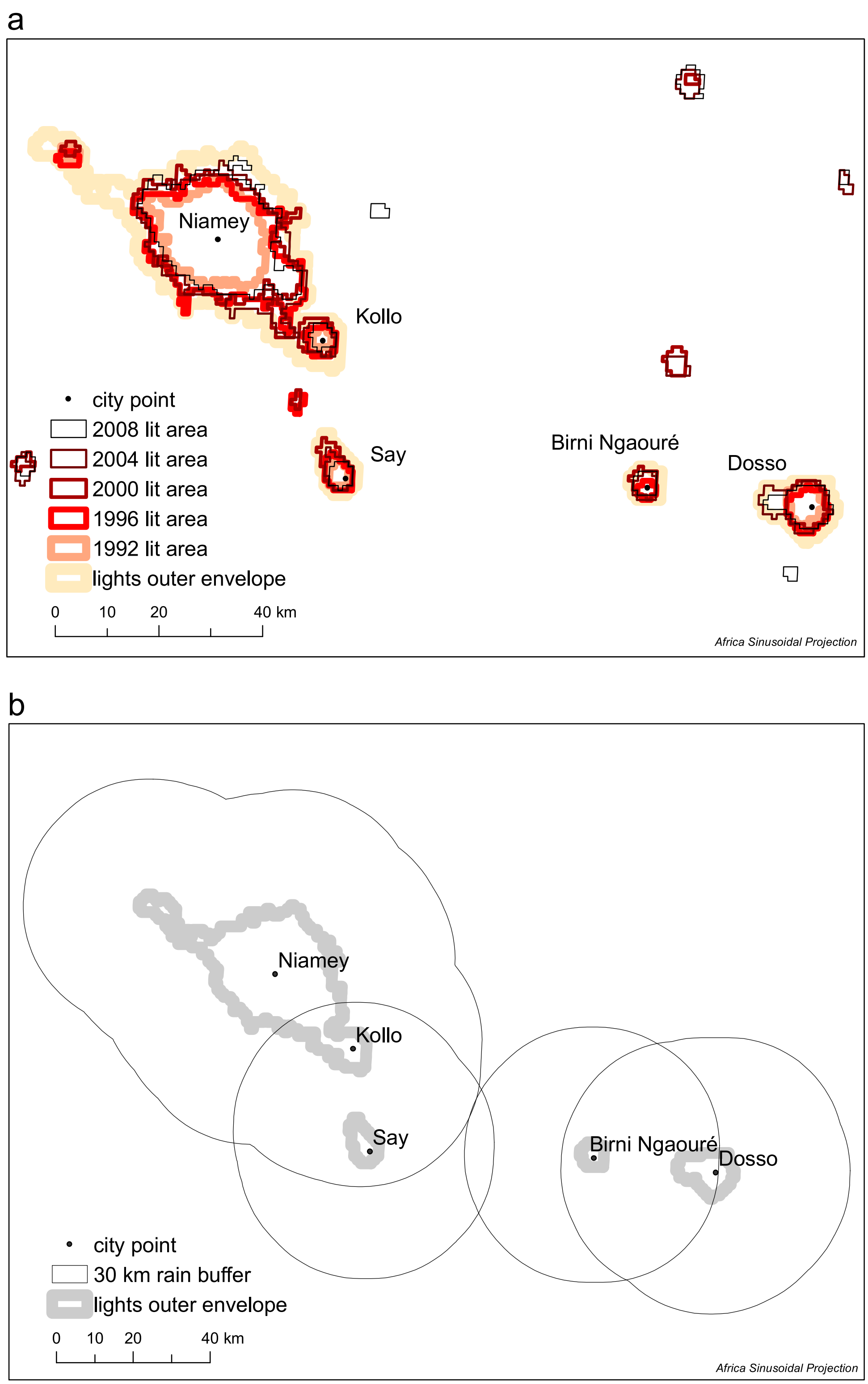

Fig. 8. Spatial data integration to obtain city level lights and rain catchment data. a. Merging lights across years and adding city points. b. 30 km rain catchment areas around city-lights.

Table 6
Change in city output and rainfall: heterogeneity by industrialization.

	(1)	(2)	(3)	(4)
Δln(rain(t))	−0.0124	−0.207***	−0.170***	−0.0798***
	(0.0124)	(0.0691)	(0.0549)	(0.0153)
Δln(rain(t))×(10 – #modern industries)		0.0199***		
		(0.00720)		
Δln(rain(t))×(14 – #all industries)			0.0116***	
			(0.00424)	
Δln(rain(t))×1(ag/GDP > 30)				0.107***
				(0.0223)

Notes: Each column is a separate regression with 1158 cities (18,528 obs). The dependent variable is Δln(lights adjusted digital number). 10 and 14 are the maximum number of modern and total industries, respectively, in any city. Robust standard errors, clustered by district, are in parentheses. All specifications include year fixed effects. *p < 0.1, **p < 0.05, ***p < 0.01.

where $light_{it}$ is light DN summed over all pixels in city i in year t[21];

$rain_{it}$ is average rainfall in millimeters per day within 30 km of city i;

X_i are time-invariant city- (or country-) level indicators for moist and industrial propensity;

$\varnothing_i$ and λ_t are city and year fixed effects; $\alpha_i t$ is a city-specific linear trend; and ε_{it} is an error term.

Eq. (2) is an annual panel specification for cities. To identify rainfall effects on lights, in principle we want to control for time-invariant city conditions, year effects (to account for annual differences in sensor settings across and within satellites), and possibly for city-specific linear growth trends. To estimate the model we first difference Eq. (2) eliminating the fixed effect in the levels equation and converting the time trend to a city fixed effect in the differenced version. This yields

$$\Delta \ln\left(light_{it}\right) = \sum_{j=0}^{k} \beta_j \Delta \ln\left(rain_{i,t-j}\right) + \sum_{j=0}^{k} \gamma_j X_i' \Delta \ln(rain_{i,t-j}) + \Delta\lambda_t + \alpha_i + \Delta\varepsilon_{it} \tag{2a}$$

We cluster errors by city to account for real and constructed serial correlation.[22] The hypothesized specification implies that each city is on a growth path and rainfall fluctuations in the local area cause it to deviate from that growth path. If climate changes are more permanent then the growth path is shifted up or down. While having individual growth paths may be appealing as a general specification, standard *F*-tests (on all columns in Table 6 to follow) cannot reject the null ($p > 0.999$) that all these city FEs are the same (i.e. that cities are on the same growth path). Thus we report results without the city FE's, noting that results are essentially identical if we add them back in.

The empirical context is different from the urbanization analysis of Section 5 in two important respects. Because we are looking at year-to-year fluctuations rather than 10–15 year changes, local income responses may be small, but empirically we do find effects. Second, because night lights data are only available after 1991, the period of analysis is shorter and starts later. This might affect the relevance of our definition of 'likely to be industrialized' from 30 years prior to 1991. We noted already the high correlation between our industry counts and manufacturing as a fraction of the urban labor force for a limited sample of 111 districts in 7 countries. Nevertheless, as an alternative measure of a district's propensity to have industry, we experiment with an indicator for whether national agriculture share in GDP (net of mineral resource rents) for 1989–1991 is less than 30%. This defines 25% of the city sample as likely to have industry.[23]

6.2. Results

Table 6 shows our basic results with heterogeneity based on having industry. As in Section 5, in column 1 the average impact of rainfall on city income (lights) overall is zero. However once we isolate the subsample of cities likely to have industry for export outside the local area, we see effects. In column 2 we use the extent of agriculture measure from the 1965 map based on modern industries. In the most industrialized areas the elasticity is now −0.21, and in zero industry areas, the elasticity is close to zero. In column 3, using the modern-industry specification results in a slightly smaller magnitude for the most industrialized areas, −0.17. If we take this −0.17 and apply the lights-GDP elasticity of about 0.3 from Henderson et al. (2012), this implies a rainfall-city product elasticity of about −0.051 for the most industrialized places. A one standard deviation rainfall increase reduces lights by 11%, and income by approximately 3.5%. In column 4, we define the likelihood of industry based on national share of agriculture, a measure that does not vary by city but is more contemporaneous. The elasticity of lights with respect to rainfall for the most industrialized countries is −0.074; so, as with our main industry measures, rainfall increases draw people out of the city and result in a loss in total city income. For less industrialized countries, the net coefficient is positive (0.028) but not significant.

A marginal increase in rainfall during a flood event is unlikely to have the same effect as other rainfall. Appendix Table A4 reports results analogous to Table 6 where we winsorize daily rainfall 2.57 city-specific standard deviations above each city's 1983–2008 mean. Coefficients on rainfall and the interaction with industry are larger in magnitude, so for example for our all-industry measure we now measure an elasticity of −0.22 (vs. −0.17) for the most industrialized areas. Eliminating extreme rainfall events does sharpen results.

In Table 7, we check first whether there is heterogeneity in the results based on whether a city is in an arid or non-arid area, again expecting potentially stronger effects in more arid areas. We divide the sample into two groups: cities above and below the median of initial rainfall. In column 1 there are sharp differences between wetter and drier areas. However as in Table 4, when we introduce industrial heterogeneity in column 2, the rainfall

[21] We address zeroes in the lights data as follows. Only 11 of 19,685 observations are positive values below 6, because of the way the lights data are cleaned by NOAA, and 3439 are zeroes. To avoid jumps when first differencing, we set all the positive values below 6 to 6 and change the zeroes to 5, before taking logs.

[22] Appendix Table A3b shows that Conley (1999) standard errors with a 500 km radius kernel are generally larger but all results of interest remain significant at 5 percent; using a smaller radius, errors are sometimes larger and sometimes smaller than clustered errors.

[23] We assume that Nigeria's agricultural share (net of resource rents) is higher than 30% based on the earliest available data, from the 2000s, when it is above 50%.

Table 7
Change in city output and rainfall: other heterogeneity and leads and lags.

	(1)	(2)	(3)	(4)
Δln(rain(t))	−0.0308**	−0.144**	−0.0725	−0.152***
	(0.0127)	(0.0574)	(0.0481)	(0.0503)
Δln(rain(t)) × (14 – #all industries)		0.00837*	0.00500	0.0112***
		(0.00441)	(0.00380)	(0.00394)
Δln(rain(t)) × 1(base rain > median)	0.0927**	−0.301		
	(0.0374)	(0.250)		
Δln(rain(t)) × 1(base rain > median) × (14 – #all industries)		0.0283		
		(0.0189)		
Δln(rain(t−1))			0.0390	
			(0.0317)	
Δln(rain(t−1)) × (14 – #all industries)			−0.00367	
			(0.00266)	
Δln(rain(t+1))				0.0478
				(0.0411)
Δln(rain(t+1)) × (14 – #all industries)				−0.00232
				(0.00337)

Notes: Each column is a separate regression with 1158 cities (18,528 obs. in cols. 1–2, 17,370 in 3–4). The dependent variable is Δln(lights adjusted digital number). 14 is the maximum number of industries in any city. 1(base rain > median) is a dummy for a 1983–1991 average rainfall value above the sample median. Robust standard errors, clustered by district, are in parentheses. All specifications include year fixed effects. $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$.

indicator shows no significant differences and we do not pursue this double heterogeneity specification further.

In columns 3 and 4, we test for lagged and lead effects, respectively, of rainfall using the all industry specification from Table 6, column 3. Leads are a placebo test; we expect no effects. Column 3 allows for lagged effects and column 4 for leads, with no evidence of either. Reassuringly, lead effects never appear in a wider set of specifications. Longer lag structures do not produce robust results, and in general the evidence for lagged effects is weak.

Finally, we examine whether effects differ for cities that are likely to be served by hydro power. Our concern is that lights could be affected directly by electricity availability and pricing, which could be affected by climate directly, independently of climate effects on income. However, because most towns are served by national grids with uniform pricing, we do not actually expect differential effects. When we fully interact our Table 6 specifications with a measure of hydropower reliance, we find no differential effect (not shown).

7. Mechanisms

We have presented reduced form evidence that climate change drives urbanization through the channel of migration toward urban employment opportunities. A literature summarized by Burke et al. (2015), has argued that such climate shocks have also generated violent conflict.[24] It is thus possible the urbanization we see is the result of people seeking the protection sometimes offered by cities, rather than their job opportunities. For this to be driving our results, this protection would need to differ between industrialized and non-industrialized cities. In this section we present evidence consistent with our model and against the conflict channel. We then turn to evidence on the migration channel itself.

7.1. Conflict

Conflict could influence urbanization in strikingly different ways depending on where it occurs. We thus use location data from the Social Conflict Analysis Database version 3.1 (SCAD; Salehyan et al., 2012),[25] which provides detailed information for local conflicts, while also recording widespread national conflicts. We match these conflict data to our lights data rather than our population data for the practical reason of the time span (it is limited to the years 1990–2013), and a theoretical one: the short term and localized nature of many conflicts makes an annual localized analysis more relevant. We exclude conflicts resulting in no deaths and those with unknown locations. We then calculate, for each of the city-years in our data, three indicators: whether a local conflict occurred within 3 km of the city or between 3 and 50 km, and whether a national conflict occurred within the encompassing country-year.[26] Summary statistics are reported in Table 1, Panel B.

Our concern is whether these added controls impact our base results in Table 6. While one might hypothesize that nearby rural conflict might draw people into the city, conflict within a city might drive them away, and widespread conflict might reduce overall economic activity, because city economic activity could impact the propensity for conflict, we do not place a strong causal interpretation on these results. We simply check whether the conflict measures alone or their interactions with our terms of interest affect our results from Section 6.

Table 8 reports the results of our Table 6 column 3 specification with these three indicators added as controls and interactions. Once again, the specification examines annual fluctuations in city lights in response to annual rainfall fluctuations in the surrounding region, allowing for heterogeneity according to the extent of industry in a city. Column 1 reproduces the Table 6 column 3 baseline. Column 2 adds to column 1 the three measures of conflict. While there is a negative correlation between national conflict and city growth, there is no effect on the terms of interest. In column 3, we add to column 2 the interactions between conflict and extent of agriculture (lack of industry). The key coefficients on changes in rainfall and those changes interacted with extent of agriculture remain little changed from column 1. The interactions between conflict and the extent of industry are insignificant. In column 4 we add a full set of interactions between rainfall changes, conflict and extent of industry. Our main terms of interest for

[24] For a dissenting view, see Buhaug et al. (2014).

[25] https://www.strausscenter.org/scad.html, accessed 2015/4/1.

[26] The 3 km buffer around the city allows for errors in georeferencing of the lights and city locations. Results are robust to varying the 50 km outer boundary of the nearby rural zone.

Table 8
Change in city output and rainfall: conflict.

	(1)	(2)	(3)	(4)	(5)
Δln(rain(t))	−0.170***	−0.168***	−0.167***	−0.207***	−0.195***
	(0.0549)	(0.0557)	(0.0551)	(0.0769)	(0.0739)
Δln(rain(t))×(14 – #all industries)	0.0116***	0.0115***	0.0115***	0.0140**	0.0124**
	(0.00424)	(0.00429)	(0.00425)	(0.00577)	(0.00557)
1(inside conflict)/1000		−28.4	−68.2***	−70.2***	24.0
		(18.1)	(24.0)	(25.7)	(31.6)
1(outside conflict)/1000		−2.39	−0.000288	10.6	−54.9
		(17.9)	(40.6)	(40.0)	(48.6)
1(national conflict)/1000		−43.9***	−32.5	−37.3	−121***
		(9.1)	(22.4)	(22.9)	(29.3)
1(inside conflict)×(14-#all ind.)/1000			3.45	3.64	−0.89
			(2.89)	(2.97)	(3.99)
1(outside conflict)×(14-#all ind.)/1000			−0.169	−0.888	6.17
			(3.59)	(3.58)	(4.33)
1(national conflict)×(14-#all ind.)/1000			−0.84	−0.556	5.01**
			(1.87)	(1.89)	(2.30)
Δln(rain(t))×1(inside conflict)/1000				11.3	8.15
				(110)	(99.1)
Δln(rain(t))×1(outside conflict)/1000				123	192
				(93.7)	(125)
Δln(rain(t))×1(national conflict)/1000				123	93.8
				(87.8)	(98.4)
Δln(rain(t))×1(inside conflict)×(14-#all ind.)/1000				2.1	−9.38
				(13.2)	(11.1)
Δln(rain(t))×1(outside conflict)×(14-#all ind.)/1000				0.44	−9.69
				(9.47)	(11.8)
Δln(rain(t))×1(national conflict)×(14-#all ind.)/1000				−8.33	−1.22
				(7.59)	(8.06)
Conflict timing	n/a	t	t	t	t−1

Notes: Each column is a separate regression with 1158 cities (18,528 obs). The dependent variable is Δln(lights adjusted digital number) in year t. 9 is the maximum number of modern and total industries, respectively, in any city. Inside conflicts are within 3 km of a city-light and outside conflicts are between 3 and 50 km. Robust standard errors, clustered by district, are in parentheses. All specifications include year fixed effects. *$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

rainfall and extent of industry are modestly larger for the base case (no conflict), but no interactions between conflict and rainfall, with or without extent of industry, are significant. In column 5 we lag the conflict measures by one year. The main effects are essentially the same as in column 4, and no conflict-rainfall terms are significant.

In summary, our rainfall and extent of industry results are not masking the effect of conflicts.

7.2. Micro evidence on migration choices of rural residents

We postulate that climate deterioration drives farmers to move into urban traded good activity, as represented by manufacturing, when such activity exists. Using various data including an annual survey of manufacturers, Colmer et al., (2016) shows that adverse annual changes in climate in India induce a reduction in farm output and also induce nearby manufacturing firms to employ more workers, especially contract or short term workers, but not in pro-labor states where hiring workers on a temporary basis is difficult. We have no reliable data to investigate the evolution of manufacturing for a substantial number of African countries over time.

DHS surveys do provide migration-related information for selected African countries; but the information is of limited usefulness here and thus we do not report a full set of results. Two potentially relevant questions are asked in most surveys: did each household member sleep at home last night, and when did surveyed adults report they began living continuously in their current place of residence.

>For the “slept last night” question, we limit analysis to rural residents in 41 surveys of 17 countries between 1992 and 2011. We use only surveys reporting cluster locations, and carried out multiple times per country, in order to account for location fixed effects. Using a linear probability model with various controls, we test whether the likelihood of a resident being away from home varies based on annual weather conditions and the degree of industrialization of nearby cities. The key limitations of these data are that we do not know the duration of or reason for the absences. Most are likely to be related to social and farm-related business trips, rather than seasonal migration. Furthermore, it is not clear when migrants are no longer classified as household members. Results for males and females are similar and are sensitive to choice of age range and the radius defining “nearby” cities. For a radius of 50 km and a sample of 25 to 49 year old males and females combined, we get a positive and significant coefficient on moisture (0.0145 with s.e. of 0.0059). However while the interaction with industry generally has the expected negative sign, it is insignificant (−0.00056 with se of 0.00043 in this example). Changing the age range or radius (to say 30 or 100 km) generally eliminates the significance of the moisture

term itself. So while the results are not inconsistent with the hypothesized mechanism, they and the test itself do not seem compelling.

For the longer-term migration question, we consider urban residents who report moving from a rural area to their present location. We now use 46 surveys in 27 countries, no longer requiring multiple surveys per country because the data from an individual survey provide a pseudo-panel across potential years of migration. Our hypothesis is that an individual's date of migration is more likely to be in a year of low rainfall near industrialized cities. There are three sets of problems with testing this. First, the hazard is incompletely specified. We cannot assign urban residents to specific rural areas, and so we can't compare them to their former rural neighbors. Second, dates of migration are subject to large recall errors. Respondents report how many years prior to the survey they moved, giving answers in whole numbers of years, with zero years explicitly corresponding to less than 365 days. Responses exhibit strong heaping at multiples of 5 years, especially beyond 5. Cox proportional hazard models for those who migrated within the last 8 years (the longest recall period not obviously subject to this heaping) provide results highly dependent on the specification. Some are consistent with the hypothesis and others are not; the experiment and the results are not compelling.

8. 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 may mitigate this risk. 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 conditions leading to greater urban population growth. However, measured effects are confined to about 20-25% of Sub-Saharan African districts with some degree of industrialization.

As our model predicts, decreased moisture increases total city populations and incomes in places whose cities are likely to have manufacturing, and are therefore more likely to be able to absorb workers leaving the farm into the urban labor force. Thus there is a strong link between climatic conditions and urbanization in particular circumstances, adding to the growing economic literature on climate and development. Our results suggest that persistent climate changes would further accelerate migration to more industrialized cities. For example, if moisture were to continue to decline at our modest sample mean rate of 0.44% per year, this would increase the annual urbanization growth rate in the most industrialized districts by 0.51 percentage points. So applying the sample mean urbanization growth rate, while a non-industrialized district that is currently 20% urban might expect to be 51% urbanized in 30 years, a highly industrialized district would be 59% urbanized. If annualized moisture decline doubled to an annual rate of 0.88%, by the end of 30 years the industrialized district would be 69% urban. While that might help industrialized districts facing moisture declines, Africa's lack of structural transformation poses greater problems in the face of climate-induced declines in agricultural productivity. To the extent that structural transformation continues to be elusive, support for agricultural adaptation becomes even more critical.

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Appendix A. Supplementary results

See Table A1–A4.

Table A1
Urbanization country sample.

Country	# units	Year 0	Year 1	Year 2	Year 3	Year 4	Censuses	missing[a]	panel units
Benin	6	1979	1992	2002			3		12
Botswana	8	1991	2001				2		8
Burkina Faso	12	1985	1996	2006			3		24
Cameroon	7	1976	1987	2005			3		14
C. Afr. Rep.	16	1975	1988	2003			3		32
Chad	14	1993	2009				2		14
Eq. Guinea	6	1983	1994				2		6
Ethiopia	11	1994	2007				2		11
Gambia	7	1993	2003				2		7
Ghana	7	1960	1970	1984	2000		4		21
Guinea	4	1983	1996				2		4
Kenya	39	1969	1979	1989			3	8	70
Kenya (2)	40	1999	2009				2		40
Lesotho	10	1986	1996	2006			3		20
Madagascar	6	1975	1993				2		6
Malawi	23	1966	1977	1987	1998	2008	5		92
Mali	8	1976	1987	1998	2009		4		24
Mauritania	13	1977	1988				2		13
Mozambique	11	1980	1997	2007			3	1	21
Niger	7	1977	1988	2001			3		14
Rwanda	9	1978	1991	2002			3		18
Senegal	8	1976	1988	2002			3		16
Sierra Leone	4	1963	1974	1985	2004		4		12
Sudan	9	1973	1983	1993			3		18
Swaziland	4	1966	1976	1986	1997		4		12
Tanzania	21	1967	1978	1988	2002		4	1	62
Togo	5	1970	1981				2		5
Uganda	38	1969	1980	1991	2002		4	8	106
Zambia	8	1969	1980	1990	2000		4	1	23
Zimbabwe	8	1982	1992	2002			3		16
Total	369		29 countries				89	19	741

[a] sample is smaller by this number in the initial intercensal period (first two in Uganda) because of some units with zero urban population.

Table A2
Varying smoothing, trimming and controls in Table 2, column 3.

Panel A	Base	Smoothing			Drop controls		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Δmoisture	−1.164***	−1.049***	−1.124*	−0.505*	−0.840**	−1.141***	−0.967**
	(0.354)	(0.377)	(0.600)	(0.295)	(0.393)	(0.348)	(0.398)
Δmoisture × (14 − #all industries)	0.0824***	0.0691**	0.0761*	0.0349	0.0617**	0.0823***	0.0656**
	(0.0263)	(0.0292)	(0.0450)	(0.0226)	(0.0289)	(0.0259)	(0.0293)
(14 − #all industries)/1000	0.131	3.60E-03	0.117	0.0347	3.52***	0.168	2.83***
	(0.727)	(0.741)	(0.779)	(0.712)	(0.436)	(0.725)	(0.562)
Initial share urban/1000	−52.0***	−50.8***	−50.9***	−50.1***		−54.8***	
	(8.15)	(8.05)	(8.13)	(7.93)		(8.21)	
ln(distance to coast)/1000	1.47	1.59	1.50	1.48			4.85**
	(1.89)	(1.89)	(1.90)	(1.89)			(1.93)
Smoothing	0-2	0-3	0-4	0-1	0-2	0-2	0-2

Notes: See notes to Table 2. All columns have 717 observations of 359 districts.

Panel B	Base	Trimming					Alt. het.
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Δmoisture	−1.164***	−1.526**	−0.860**	−0.907***	−1.151***	−1.089***	−0.175
	(0.354)	(0.596)	(0.335)	(0.339)	(0.349)	(0.289)	(0.193)
Δmoisture × (14 - #all industries)	0.0824***	0.118***	0.0716***	0.0663***	0.0855***	0.0770***	
	(0.0263)	(0.0437)	(0.0245)	(0.0254)	(0.0254)	(0.0220)	
(14 - #all industries)/1000	0.131	−1.87	−0.200	−6.57E-03	0.149	0.483	
	(0.727)	(1.180)	(0.769)	(0.731)	(0.737)	(0.702)	
Initial share urban/1000	−52.0***	−77.0***	−56.4***	−52.8***	−51.9***	−48.1***	
	(8.15)	(15.1)	(9.18)	(8.34)	(7.93)	(6.95)	
ln(distance to coast)/1000	1.47	2.02	2.18	2.11	1.40	0.723	3.09**
	(1.89)	(1.88)	(1.85)	(1.86)	(1.87)	(1.56)	(1.53)
Δmoisture × 1(low urban)							0.0877
							(0.195)
1(low urban)							0.0216***
							(0.00302)
Observations	717	741	733	725	709	677	717
Trimmed	24	0	8	16	32	64	24
Smoothing	0-2	0-2	0-2	0-2	0-2	0-2	0-2
districts	359	369	366	363	356	350	359

Notes: See notes to Table 2. 1(low urban) is a dummy for the bottom 4 quintiles of the cross-sectional distribution of initial share urban. *p < 0.1. **p < 0.05. ***p < 0.01.

Table A3a
Table 2 with Conley (1999) standard errors.

	(1)	(2)	(3)
Δmoisture	−0.0761	−1.064***	−1.164***
	(0.146)	(0.395)	(0.380)
Δmoisture × (9 − #modern industries)		0.116***	
		(0.0391)	
Δmoisture × (14 − #all industries)			0.0824***
			(0.0249)
(9 − #modern industries)/1000		−0.51	
		(1.41)	
(14 − #all industries)/1000			0.131
			(0.787)
Initial share urban/1000	−48.9***	−55.0***	−52.0***
	(7.22)	(8.48)	(8.08)
ln(distance to coast)/1000	1.43	1.55	1.47
	(1.59)	(1.66)	(1.66)
Observations	717	717	717
R-squared	0.605	0.607	0.607

Notes: See notes to Table 2. Conley (1999) standard errors in parentheses (500 km radius uniform kernel). *$p < 0.1$. **$p < 0.05$. ***$p < 0.01$.

Table A3b
Table 6 with Conley (1999) standard errors.

	(1)	(2)	(3)	(4)
Δln(rain(t))	−0.0124	−0.207***	−0.170***	−0.0798***
	(0.0184)	(0.0772)	(0.0635)	(0.0299)
Δln(rain(t)) × (10 − #modern industries)		0.0199**		
		(0.00803)		
Δln(rain(t)) × (14 − #all industries)			0.0116**	
			(0.00486)	
Δln(rain(t)) × 1(ag/GDP > 30)				0.107***
				(0.0397)
Observations	18,528	18,528	18,528	18,528
R-squared	0.156	0.156	0.156	0.156
radius (km)	500	500	500	500

Notes: See notes to Table 6. Conley (1999) standard errors in parentheses (500 km radius uniform kernel). *$p < 0.1$. **$p < 0.05$. ***$p < 0.01$.

Table A4
Table 6 with winsorized rainfall.

Variables	(1) Δln(lights)	(2) Δln(lights)	(3) Δln(lights)	(4) Δln(lights)
Δln(rain(t))	−0.0188	−0.277***	−0.220***	−0.100***
	(0.0146)	(0.0813)	(0.0659)	(0.0187)
Δln(rain(t)) × (10 − #modern industries)		0.0264***		
		(0.00847)		
Δln(rain(t)) × (14 − #all industries)			0.0148***	
			(0.00507)	
Δln(rain(t)) × 1(ag/GDP > 30)				0.128***
				(0.0271)

Notes: See notes to Table 6. Daily rainfall winsorized at 2.57 standard deviations above the daily rainfall mean. *$p < 0.1$. **$p < 0.05$. ***$p < 0.01$.

Appendix B. A model of the impact of climate variability on local urbanization

B1. The basic model

B1.1. Urban sector

The urban sector (city) produces services, which are not traded across districts, and it may or may not produce manufactures that are potentially tradable across districts. Services output per unit labor is b. When it exists, manufacturing output per worker is cL_M^{ε}, where L_M is total labor units in manufacturing and $\varepsilon > 1$. Services, produced with constant returns to scale, represent non-agricultural items produced and sold locally, but not traded outside the district. Scale economies in manufacturing, represented by ε, can come from information spillovers or from diversity of local intermediate inputs in a monopolistic competition framework.[27] Final output of manufactures is tradable nationally or internationally at prices fixed for the city. The wage rate per unit labor in the city is thus

[27] In the latter context, output of any final goods firm is $m = \left(\int_0^n z(h)^{1/(1+\varepsilon)} dh\right)^{1+\varepsilon}$ where output of any intermediate input producer employing $l(h)$ workers is $z(h) = \gamma l(h) - \lambda$ and n is the number of local intermediate input producers a city can support. Solving the monopolistic competition problem, the equilibrium wage of a worker in the manufacturing sector has the form cL_M^{ε}.

$$w = p_S b = cL_M^{\varepsilon} \tag{B1}$$

where p_S is the price of services and manufacturing is the numeraire.

Following standard urban models (Duranton and Puga, 2004; Desmet and Henderson, 2015) in modeling urban diseconomies, we assume workers live in a city where they must commute to work in the city center. Each worker is endowed with 1 unit of labor and commuting reduces time spent working at a rate of $4t$ per unit distance commuted. Those living far from the city center spend less on land rents to compensate for their higher commuting costs, or lost labor earnings. City land rents are redistributed to urban workers. Per-worker net income, after commuting and land rents are paid and land rent income is redistributed, is

$$y = w(1 - tN_U) = p_S b(1 - tN_U) \tag{B2}$$

where N_U is city population.[28] As city scale rises, per-worker time for production declines, a representation of the basic urban diseconomy. City effective total labor supply net of time spent commuting, L, is

$$L_S + L_M = L = N_U(1 - tN_U) \tag{B3}$$

where L_S is the labor force in services.

B1.2. The rural sector and equilibrium conditions for the district

The other part of the district is the rural sector producing agricultural products, sold at a fixed price p_A in international markets. Per-worker income in the agricultural sector is given by

$$p_A f(N_A, R), \quad f_1 < 0, \; f_2 > 0. \tag{B4}$$

The rural (agricultural) population is N_A and the total land area is shared equally among that population. Per-worker output (either marginal or average output depending on how agricultural rents are distributed) is declining in total farm workers and increasing in moisture or rainfall, R.

Migration arbitrage between the urban and rural sectors equalizes incomes and there is full employment in the district so that

$$p_S b(1 - tN_U) - p_A f(N_A, R) = 0 \tag{B5}$$

$$N_A = N - N_U \tag{B6}$$

N is district total population. The model is closed by noting that the untraded services market must clear. Total production is bL_S and total demand is $N\, D(y, p_A, p_S)$ for the individual demand function $D(y, p_A, p_S)$. Thus we know using (B2) and (B5) that

$$bL_S = N \; D(p_A f(N_A, R), \; p_A, \; p_S) \tag{B7}$$

B2. Comparative statics when the local urban sector exports manufacturing

We seek the effect of moisture change on city (or conversely agricultural) population and total city income. That is, we want to solve for dN_U/dR and $d(y\,N_U)/dR$.

B2.1. Changes in urbanization

First we solve for the effect on the population allocation. We differentiate (B1), (B7), (B3) and (B5), having used (B6) to substitute for N_A. We define income and own-price elasticities of demand for services, $\eta_y > 0, \; \eta_{p_S} < 0$ in the usual fashion. We then solve these equations to get the basic comparative static[29]

$$\frac{dN_U}{dR} = \frac{f_2}{f} \quad \frac{L_M + \varepsilon L_S(\eta_y + \eta_{p_S})}{Z} \tag{B8}$$

where $Z \equiv \frac{f_1}{f}\left[L_M + \varepsilon L_S\left(\eta_y + \eta_{p_S}\right)\right] - \frac{t}{1 - tN_U}\left(L_M + \varepsilon L_S \eta_{p_S}\right) + \varepsilon(1 - 2tN_U)$.

To sign this expression we first sign Z by imposing stability. The issue of stability arises because of urban scale economies. In the traditional framework, real city income is an inverted-U shaped function of city size, and equilibria to the left of the peak are potentially unstable. We generally restrict our attention to stable equilibria, and discuss scale economies below. Stability of migration between the urban and rural sectors requires that the differential in (B5) be decreasing in N_U. This reduces to

$$Z\left(L_M + \varepsilon L_S \eta_{p_S}\right)^{-1} < 0. \tag{B9}$$

As long as the local urban manufacturing sector is not negligible (i.e. $L_M/L_S$is not too small) then $(L_M + \varepsilon L_S \eta_{p_S}) > 0$. For example if $\eta_{p_S} = -1$, we require that $L_M/L_S > \varepsilon$. Estimates of ε in the literature are typically 0.05 or less (Combes and Gobillon, 2015), so as long as the local city has a modicum of manufacturing, $L_M + \varepsilon L_S \eta_{p_S} > 0$, and stability implies $Z < 0$. We focus on this case here, and the opposite case with little or no manufacturing later.

Returning to (B8), given $L_M + \varepsilon L_S \eta_{p_S} > 0$ and therefore $Z < 0$, $dN_U/dR < 0$ follows directly. The magnitude of response depends on the magnitude of f_2/f . Of course, as moisture changes all variables change, but we can say that as f_2 approaches zero, so does the response. f_2/f plays a role in the empirical formulation in Section 5.

B2.2. Changes in city income

The effect of moisture change on total city income, $yN_U = p_A f(N - N_U, R)\, N_U$, is

$$\frac{dyN_U}{dR} = p_A f_2 Z^{-1}(1 - tN_U)^{-1} * M \tag{B10}$$

where $M \equiv [L_M + \varepsilon L_S(\eta_y + \eta_{p_S})](1 - 2tN_U) + tN_U \varepsilon L_S \eta_y$
$\qquad + N_U \varepsilon(1 - 2tN_U)(1 - tN_U)$.

Under the current assumption that $L_M + \varepsilon L_S \eta_{p_S} > 0$, $Z < 0$. If we further require that city earned incomes $(1 - 2tN_U)$ be positive, M must be positive. Given that Z is negative, dyN_U/dR is negative. Income is nominal in a context where the price of services will change, but for a broad class of utility functions, the city's sum of utilities is affected in

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[28] Following Duranton and Puga (2004), in a linear city, where each worker is endowed with 1 unit of time and working time is $1 - 4tu$ where u is distance from the city center and $4t$ unit commuting costs, it is easy to derive expressions for city labor force L (by integrating over the two halves of the city each of length $N_U/2$), for the city rent gradient (equating rent plus commuting costs for a person at u with that of a person at the city edge where rents are 0, so they are equally well off in equilibrium) and for total rents, each as a function of population N_U. These have forms respectively: $L = N_U(1 - tN_U); \; R(u) = wt(2N_U - 4u); \; \text{total rents} = wtN_U^2$

where w is the wage rate. A person living at the city edge and paying zero rent earns in net $w(1 - 2tN_U)$, with the diseconomy arising from increasing commuting distances reducing time available to work. After getting a share in urban rent income their net income is $y = w(1 - tN_U)$.

[29] Differentiating these four equations gives (a) $\frac{dp_S}{p_S} = \varepsilon \frac{dL_M}{L_M}$, (b) $\frac{dL_S}{L_S} = -\eta_y \frac{f_1}{f} dN_U + \eta_y \frac{f_2}{f} dR + \eta_{p_S} \frac{dp_S}{p_S}$, (c) $dL_S + dL_M = (1 - 2tN_U)dN_U$, and (d) $\frac{dp_S}{p_S} - \frac{t}{1 - tN_U} dN_U + \frac{f_1}{f} dN_U - \frac{f_2}{f} dR = 0$. Using (a) and (b) to substitute for dL_M and dL_Sin (c), we solve for $\frac{dp_S}{p_S} = \varepsilon \left[1 + \varepsilon \frac{L_S}{L_M} \eta_{p_S}\right]^{-1} \left(\left[\frac{1 - 2tN_U + L_S \eta_y f_1/f}{L_M}\right] dN_U - \frac{L_S}{L_M} \eta_y \frac{f_2}{f} dR\right)$, and substitute this into (d) to get equation (B8).

qualitatively the same way as city income.[30] In sum we have the following proposition relevant to our empirical work:

Proposition 1. *If the city has a tradable manufacturing sector that is not too small relative to its local service sector so that* $L_M + \varepsilon L_S \eta_{p_S} > 0$, *a decline in moisture will lead to an increase in urban population and total city income.*

B3. Comparative statics with no or minimal local manufacturing

If the local traded goods manufacturing sector is very small so $L_M + \varepsilon L_S \eta_{p_S} < 0$, then the fortunes of the city are tied to the local agricultural sector, as in Jedwab (2013).[31] Stability thus requires $Z > 0$, and the sign of dN_U/dR in eq. (B8) is ambiguous. If $\eta_y + \eta_{p_S} \geq 0$, then $dN_U/dR > 0$ whether L_m is zero or small. When $L_m = 0$, the sign of dN_U/dR is the same as the sign of $\eta_y + \eta_{p_S}$. Ambiguity arises when both $\eta_y + \eta_{p_S} < 0$ and $L_m > 0$. In terms of magnitude, we can say that if $\eta_y + \eta_{p_S} = 0$, as $L_M \to 0$, $dN_U/dR \to 0$. There is little effect of moisture on the rural-urban population allocation because migration effects only come through changes in demand for services (and the effect of reduced price on demand for services is offset by the effect of reduced per person income).

However, (B10) suggests that total urban income more generally increases with moisture. Given $Z > 0$, if $\eta_y + \eta_{p_S} \geq 0$, we can unambiguously show that $dyN_U/dR > 0$. Increased rainfall raises local farm productivity and all local incomes.[32] With city population modestly affected, total city income must rise. However, if $\eta_y << \left|\eta_{p_S}\right|$, so that city population declines a lot, then total urban income may decline as well.

Proposition 2. *If the city has a tiny or non-existent traded manufacturing sector so that* $L_M + \varepsilon L_S \eta_{p_S} < 0$, *the effect of a decline in moisture on city population is ambiguous and tends to zero as* $L_M \to 0$ *when* $\eta_y + \eta_{p_S} = 0$ *. Total city income declines as long as* $\eta_y + \eta_{p_S}$ *is not strongly negative.*

Appendix C. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.jdeveco.2016.09.001.

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[30] We examine the sum of utilities based on a log linear indirect utility function, but it applies to any indirect utility function where doubling income doubles utility. For $V(y, \vec{p})N_U = AN_U y p_S^{-\sigma S}$, where σ_S is the expenditure share of services, we can show that $\frac{d(N_U y p_S^{-\sigma S} A)}{dR} = p_S^{-\sigma S} AN_U y \frac{f_2}{f} Z^{-1}\left[(1-\sigma_S)\varepsilon(1-2tN_U) + \frac{(1-2tN_U)(L_M+\varepsilon\eta_{p_S}L_S)+[1-(1+\sigma_S)tN_U]\varepsilon\eta_y L}{(1-tN_U)N_U}\right]$. If $Z < 0$ this expression is negative. For completeness, we note the expression for the change in city per capita income is: $\frac{dy}{dR} = p_A f_2 Z^{-1}\left[-(L_M+\varepsilon L_S\eta_{p_S})\frac{t}{1-tN_U} + \varepsilon(1-2tN_U)\right]$. In the current situation, given $Z < 0$, $L_M + \varepsilon L_S \eta_{p_S} > 0$, and the definition of Z, $dy/dR > 0$. As noted below, we cannot measure per capita income in our empirical context, as our total income change proxy is defined at temporal scales for which no corresponding population change data exist.

[31] We describe this case assuming the local manufacturing sector exists, but the situation is analogous in the case where there is no manufacturing at all and per-worker output of the service sector is given by $bL_S^{\varepsilon_S}$, $\varepsilon_S \geq 0$.

[32] See the expression for changes in per capita income above.

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