A Research Series on Economic Development in India
No. 1

CHARTER CITIES INSTITUTE

# Soaked Cities

## CLIMACTIC MOISTURE AND URBANIZATION PATTERNS IN INDIA FROM 1971–2011

**Eva Klaus,** August 2023

CHARTER CITIES
INSTITUTE

## THE FUTURE OF DEVELOPMENT

**Empowering new cities with better governance to lift tens of millions of people out of poverty.**

The Charter Cities Institute is a non-profit organization dedicated to building the ecosystem for charter cities by:

- Creating legal, regulatory, and planning frameworks;
- Advising and convening key stakeholders including governments, new city developers, and multilateral institutions;
- Influencing the global agenda through research, engagement, and partnerships.

# TABLE OF CONTENTS



**Acknowledgments**

Thank you to Professor Matthew McCartney, Professor Sam Asher, and Professor Giovanna M.D. Dore for their invaluable comments and feedback on earlier versions of this paper. Thank you also to Christy Kingsbury for her work on the graphics and to Laura Rostad for her support in copy-editing.

# 1 INTRODUCTION AND MOTIVATION

**Over the coming decades, urbanization and climate change will profoundly transform our world; however, these two powerful phenomena are projected to have a particularly large impact on developing countries. Cities are currently home to over half of the world's population, but the UN Framework Convention on Climate Change projects they will accommodate over 70 percent of the total population by 2050, with the overwhelming majority of urban growth concentrated in countries across Africa, Asia, and South America (UNFCC 2017). Rapidly burgeoning urban centers may pose major challenges for national and municipal governments struggling to keep up with the pace of expansion and growing demand for public services. Historically, unplanned urban growth has resulted in the "proliferation of slums, congestion, pollution, lack of affordable housing, poor access to sanitation and waste management, and vulnerability to natural hazards" (World Bank 2021).**

As a result, rapid and unsustainable urbanization "could make the world's society and economy increasingly vulnerable to the impacts of climate change…, [particularly] urban centers… in developing countries" (UNFCC 2017). Indeed, the United Nations warns that the "effects of urbanization and climate change are converging in dangerous ways" (UN Habitat [n.d.]). For example, hasty, unsupervised, and unsound construction may increase the likelihood of damage to infrastructure and dwelling units during severe storms, which are projected to become increasingly intense and unpredictable as climate change continues (IPCC 2022, 938). Similarly, land degradation resulting from urban sprawl may heighten susceptibility to devastating landslides during periods of heavy rainfall (Ozturk et al. 2022).

Rising temperatures also threaten to turn cities into urban heat islands; recent work by Tuholske et al. (2021) finds that between 1982 and 2016, global exposure to extreme heat in urban areas "increased nearly 200%, affecting 1.7 billion people." Remarkably, 52.4 percent of the increase in exposure to extreme heat in urban areas was concentrated in India alone, due to both the country's rapid urban population growth and its vulnerabilities to climate change (Tuholske et al. 2021, Appendix).

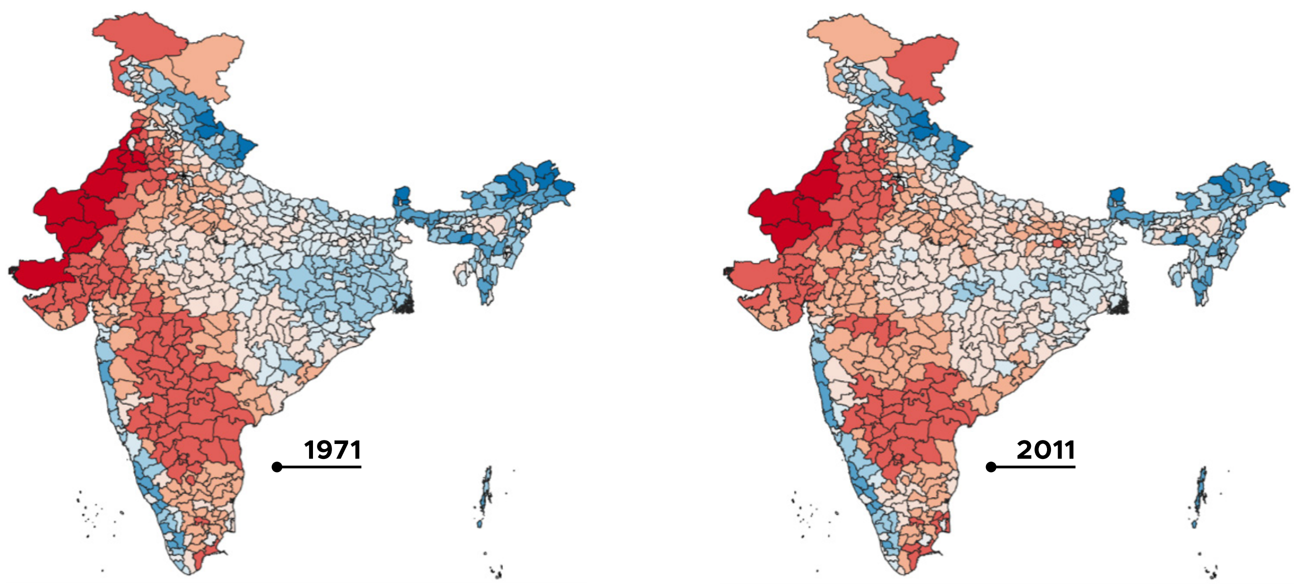
On the other hand, sustainable urbanization has the potential to foster human flourishing at all levels and support climate adaptation efforts.[1] In fact, there is "a near-perfect correlation between urbanization and prosperity across nations. On average, as the share of a country's population that is urban rises by 10 percent, the country's per capita output increases by 30 percent" (Glaeser 2011, 7). Cities, at their best, are epicenters of opportunity, innovation, and economic growth. As such, they play an important role in the fight against climate change. For one, individuals and households whose livelihoods stand to be negatively impacted as climate change "reshapes the comparative advantage of regions" will increasingly rely on urban centers for alternative employment opportunities and stability (Adger et al. 2020). For example, work by Rigaud et al. (2018) at the World Bank finds that climatic variability, drought, and other hazards caused by climate change will negatively impact agricultural livelihoods in South Asia – a region projected to see 35.6 million internal climate migrants by 2050 – leading to urban migration as people seek alternative sources of income (90). Furthermore, efficient and informed urban planning can also enable households to better withstand the impacts of climate change through high-quality public service provision – such as water and sanitation services, electricity, and waste management – and sound infrastructure and dwelling construction. Finally, the knowledge sharing and innovation that arises from urban agglomerations has the potential to spur the development of new green technologies that support climate resilience in both urban and rural areas.

Managing urbanization and adequately preparing cities for rapid growth will allow citizens to harness the economic opportunities that come with urban development and help improve overall climate resilience. Christiaensen, De Weerdt, and Todo (2013) point out that "how the world urbanizes may well be as important as urbanization itself." As such, it is essential to understand how urbanization and climate change will interact to compound growing population pressures on urban areas. Existing literature suggests that climate change may influence urbanization dynamics and city growth in a variety of ways.[2] For one, regions experiencing higher temperatures, drier conditions, or more extreme weather patterns may see declines in agricultural productivity, driving rural-to-urban migration or rural out-migration as residents engaged in agriculture search for new employment opportunities (Henderson, Storeygard, and Deichmann 2017; Barrios, Bertinelli, and Strobl 2006). Alternatively, regions experiencing milder conditions may see agricultural productivity gains and rural growth, leading to population and savings spillovers into nearby cities, thus contributing to greater urban population growth (Bustos, Garber, and Ponticelli 2019; Asher et al. 2022). Recent research suggests that these two processes may, in fact, occur simultaneously and in close proximity to one another (Tuholske et al. 2019).

This study makes an original contribution to this debate by exploiting district-level heterogeneity in climatic moisture to estimate the impact of climate change on urbanization and city growth in India between the years of 1971 and 2011 (see Figure I).[3]

The central contention of this study is that changes in climatic moisture are exogenous and directly impact agricultural productivity, which subsequently influences urbanization patterns by either pushing rural residents into urban areas or supporting nearby city growth through spillovers. The guiding research question is thus divided into two parts regarding how climate change affects: (i) district-level urbanization patterns and (ii) city-level population growth across India.[4] To answer these questions, two 40-year datasets are constructed from census data, climatic and meteorological data, and industry-related carbon emissions data. The first dataset aggregates population statistics to the district level, resulting in a balanced panel of 485 districts. This is used to estimate the effect of climatic moisture changes on the share of the population living in urban centers, urban population growth, and rural population growth at the district level. The second dataset is constructed at the city level, resulting in a balanced panel of 2,222 urban centers throughout India; this is used to estimate the effect of climatic moisture changes on city population growth.[5] An important difference between these two datasets is that while the first accounts for the classification of new urban centers over time, the second includes only cities that were classified in the 1971 census.[6]

**FIGURE I**
Moisture Map of India, 1971–2011




*Source*: Author's calculations using data from Willmott and Feddema's Moisture Index and the 2011 Census of India. This map shows the average Moisture Index score for each district. Districts that are dark red have lower moisture scores, representing drier conditions. Districts that are dark blue have higher moisture scores, representing wetter conditions. The 1971 map is displayed on the left and the 2011 map on the right. Districts in gray have no gridded observations in Willmott and Feddema's data archive.

This study finds evidence that declines in climatic moisture – alternatively referred to as "drying" – leads to greater growth in urbanization across districts in India. However, the effect of climatic moisture decline on a district's total urban population growth is statistically insignificant. Instead, evidence suggests that districts experiencing drying have slower rural population growth compared to districts with increased climatic moisture. As such, the observed increase in the rate of urbanization in drying districts may be partially due to rural out-migration to districts with land more suitable to agriculture, potentially contributing to the observed increase in rural population growth in moister districts. This is consistent with the literature and the Indian context, where substantial frictions exist in sectoral labor reallocation and rural-to-urban migration is slow (Liu, Shamdasani, and Taraz 2020). Moreover, this study also finds strong, statistically significant evidence that established cities have grown most rapidly in districts experiencing increased moisture. This is largely consistent with the findings of Asher et al. (2022). Taken together, these findings suggest that districts in India experiencing drying may become increasingly urbanized, but major population pressures will likely arise in urban centers and rural regions located in districts experiencing moisture growth.

This study contributes to the literature in three important ways. For one, most scholarship at the nexus of urbanization and climate change employs cross-country regression methods. This study exploits within-country heterogeneity in climatic moisture changes to investigate internal urbanization patterns. Focusing on a single country also has the advantage of removing unobserved cross-country heterogeneity. Second, this study considers the effect of changes in moisture on urbanization, as opposed to precipitation or rainfall, which are the most common proxies for climate change. This is an important contribution, as moisture is arguably a more pertinent measure for estimating the effect of climate change on atmospheric agricultural potential and thus agricultural productivity. Finally, this study goes beyond the consideration of urban share growth to investigate rural and city-level dynamics. These findings have important implications for understanding how climate change may alter or compound population pressures on urban centers.

Nonetheless, this study also suffers from several shortcomings. For one, it does not directly observe district-level agricultural output. Although there are limited data available on agricultural yields for recent years, consistent and accurate time-series data on yields over the period examined are not readily available. Instead, this study finds its theoretical underpinnings in the abundant climatology literature, which provides evidence for the close relationship between climatic moisture and agricultural potential (Kumar and Gautam 2014; Abiy et al. 2019; Gornall et al. 2010). Additionally, this study does not directly measure internal migration patterns, nor does it consider seasonality in migration, primarily focusing on permanent, district-level local migration instead. Although it is true that rural to urban migration patterns vary across regions, states, districts, and cities – for example, some destinations attract migrants from across the country, while others pull primarily from nearby populations – the goal of this paper is to understand how climatic changes impact local urbanization dynamics and city growth. Finally, the use of annual averages for moisture, temperature, and precipitation may obscure seasonal fluctuations and extreme weather events, which can devastate crop yields and directly influence internal migration patterns. Nonetheless, this study is concerned primarily with long-run, slow-onset climatic changes, so annual averages in climatic moisture are the more pertinent measure. Future studies may seek to overcome these limitations by employing data on crop yields, directly observing internal migration and demographic dynamics, constructing average measures for climatic moisture during the wet and dry seasons, and considering exposure to extreme weather events.

The rest of this paper is structured as follows: Section Two surveys the existing literature on the relationship between climate change and urbanization; Section Three provides an overview of the empirical strategy, including the relevance and construction of the climatic moisture index, data sources, and empirical specification; Section Four outlines the main findings of this study; Section Five discusses the results and proposes an agenda for future research; Section Six concludes.

# 2 LITERATURE

A growing body of research suggests there are clear yet nuanced relationships between climate change and urbanization patterns. For one, regions negatively impacted by climate change may experience higher rates of urbanization, with declining climatic and environmental conditions acting as a "push" factor driving rural residents into nearby cities in search of alternative off-farm employment opportunities. Several recent studies support this argument. Henderson, Storeygard, and Deichmann (2017) present evidence that there are "strong, but differentiated links between climate and urbanization." More specifically, these authors find that districts in countries throughout Sub-Saharan Africa that experienced greater loss in moisture, but had a more robust industrial presence, experienced greater urbanization, measured as growth in urban population share, leading them to argue that local "urban migration provides an 'escape' from negative agricultural moisture shocks." Furthermore, Barrios, Bertinelli, and Strobl (2006) find that decreases in rainfall increase urbanization rates in countries across Sub-Saharan Africa. Using global data, Peri and Sasahara (2019) argue that increases in temperature may have differential effects on urban migration depending on a country's socioeconomic status. They find evidence that higher temperatures increase internal migration to urban areas in middle-income countries but decrease rural to urban migration in countries situated in the bottom quartile of the income distribution. Bohra-Mishra, Oppenheimer, and Hsiang (2014) find that higher temperatures have contributed to permanent out-migration from warming provinces in Indonesia.

Nonetheless, not all regions have been, or are projected to be, equally impacted by climate change. While some areas may experience increasingly adverse climatic conditions, others may benefit from milder conditions. As such, regions experiencing more favorable climatic and meteorological conditions may experience improved agricultural productivity, leading to local economic growth and potentially subsequent urbanization. In this way, changes such as increased climatic moisture may act as a "land-augmenting technological change" that "leads to an increase in the marginal product of labor in agriculture" (Bustos, Caprettini, and Ponticelli 2016). This may lead to increases in rural population growth, as more amenable land attracts rural migrants from areas where land has become less suitable to agriculture. Recent work by Asher et al. (2022) finds that villages in India with better access to canals – a land-augmenting technology that increases agricultural productivity – have "higher population density [which is evidence of] increased demand for [agricultural] labor." The authors present compelling evidence that there are "concentrated population gains in proximate urban areas…[despite] net population gains [that seem to be] considerably higher in rural areas than in urban areas."

The burgeoning rural population may migrate into local cities, but high agricultural yields may also contribute indirectly to the growth of nearby urban centers. In a setting such as India, where "rural-urban mobility is low and structural transformation, particularly the movement from agriculture to manufacturing is slow and 'stunted,'" agricultural gains may also contribute to urban growth through the flow of increased rural savings and subsequent investment (Liu, Shamdasani, and Taraz 2020). Bustos, Garber, and Ponticelli (2019) find evidence that "agricultural productivity growth can lead to structural transformation through its impact on capital accumulation," as more savings are made available to financially integrated urban centers. In this way, climate change–induced agricultural productivity gains may lead to structural transformation in urban centers as a byproduct of rural growth.

Taken together, these two strands of literature provide evidence that urbanization patterns may be impacted by climate change in two important ways: regions experiencing increasingly adverse climatic and meteorological conditions may see a higher proportion of the population concentrated in urban areas as rural residents are "pushed" to find off-farm employment; and regions experiencing climatic changes more amenable to agricultural productivity may see urban population gains in nearby cities as the entire region grows and thrives. Recent work by Tuholske et al. (2019) finds evidence of such a complex relationship between climatic conditions, city size, and urban growth patterns. Using gridded population data and a robust method of urban identification, the authors present evidence that "small and medium-sized urban settlements in arid regions are growing faster compared to larger urban settlements across Africa's arid regions…By comparison, in semi-arid and humid regions of Africa, larger cities are absorbing a greater share of urban population growth." In essence, secondary and tertiary cities have emerged in drier regions throughout Africa, while city populations have exploded in wetter regions. The authors' conclusions provide a neat bridge between the primary strands of work on climate change and urban growth patterns, suggesting that climatic conditions may give rise to two distinct forms of urbanization, which can occur simultaneously and in close proximity to one another. In concert with the study conducted by Henderson, Storeygard, and Deichmann (2017), these findings also provide support for the relevance of climatic moisture as a driver of urbanization.

This study contributes to the growing body of literature that employs climatic moisture as a proxy measure for climate change and investigates its impact on urbanization and urban growth. However, in contrast to the studies conducted by Henderson, Storeygard, and Deichmann (2017) and Tuholske et al. (2019), this study focuses solely on within-country heterogeneity in moisture growth as opposed to cross-country differences. Furthermore, it considers the simultaneous yet differentiated processes of urbanization and urban growth, as opposed to previous studies, which often consider only one or the other.

# 3 EMPIRICAL APPROACH

### 3.1 RELEVANCE OF CLIMATIC MOISTURE

A majority of the literature investigating the impacts of climate change on urbanization patterns measures climatic conditions using data on precipitation or temperature; however, there are three distinct advantages of estimating climatic variability and change using moisture:

- It is highly reflective of long-term climatic changes
- It is closely related to agricultural potential
- It is a good source of exogenous heterogeneity, particularly across districts in India

C. W. Thornthwaite was one of the first climatologists to recognize the importance of atmospheric water balance in the assessment and classification of climatic conditions, arguing that "the combined evaporation from the soil surface and transpiration from plants, called evapotranspiration," is a critical and often-overlooked part of the hydrological process (Thornthwaite 1948). Furthermore, Thornthwaite argued that it is not only necessary to track the actual movement of water "from the Earth to the atmosphere" (ibid.), but also the "evapotranspiration that would occur if the vegetation experiences no water stress" (Willmott and Feddema 1992). Thus, "potential evapotranspiration" – according to Thornthwaite's construction – may also be understood as the water required by a hypothetical, full-cover reference plant, given typical meteorological conditions for a region, such that no water is returned to the atmosphere through evapotranspiration.

Comparing potential evapotranspiration to precipitation levels, Thornthwaite argued, would provide valuable information on the dryness or wetness of the climate: "As water deficiency becomes larger with respect to potential evapotranspiration, the climate becomes arid; as water surplus becomes larger, the climate becomes more humid" (Thornthwaite 1948).

Following from this observation, Thornthwaite put forth a method for estimating a moisture index based on the ratio between precipitation and potential evapotranspiration – which may also be interpreted as an "aridity index" – to measure long-run climatic tendencies toward water deficiency or surplus. Willmott and Feddema (1992) subsequently proposed a modified version of Thornthwaite's index that lends itself to clearer interpretation.[7] Their Moisture Index is defined as follows:

$$I_m = \begin{cases} \left(\frac{r}{E^\circ} - 1\right), & r < \mathrm{E}^\circ \\ \left(1 - \frac{E^\circ}{r}\right), & r \geq \mathrm{E}^\circ \end{cases},$$

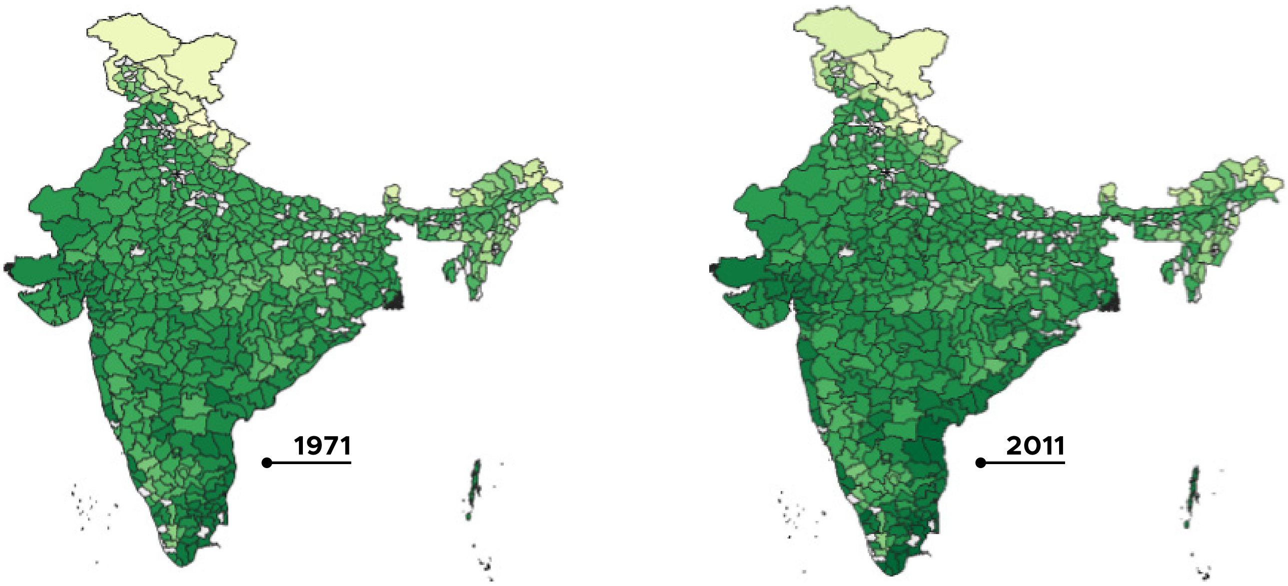
where $r$ is the average monthly precipitation rate and $E^o$ is the average monthly potential evapotranspiration. Estimating potential evapotranspiration is a complex process for which multiple methods have been proposed. In this model, potential evapotranspiration is calculated as a function of spatially-interpolated meteorological data – specifically, temperature, humidity, windiness, and solar radiation – using the method proposed by Shuttleworth and Wallace (1985), as it has been found to perform well across regions in different climatic zones (Stannard 1993; Abeysiriwardana, Muttil, and Rathnayake 2022).[8] This calculation yields a symmetric index ranging from -1 to 1, such that negative scores correspond to a deficiency of moisture relative to atmospheric demand and positive scores correspond to a moisture surplus relative to atmospheric demand.[9]

Using Willmott and Feddema's Moisture Index to proxy climate change has a variety of advantages over more commonly used measures such as temperature and precipitation. For one, climatic moisture provides a stable measure of slow-onset climatic changes. Neither potential evapotranspiration nor mean precipitation are highly volatile measures; as such, they reflect long-run, enduring changes in "mean climate state" as opposed to extreme events (Gornall et al. 2010).

As climate change continues, scientists predict that for every additional degree Celsius of warming, the atmosphere will be capable of holding up to 7 percent more water, resulting in increased evaporation of surface moisture (Buis 2022; Kumar and Gautam 2014). In other words, evapotranspiration and potential evapotranspiration are expected to increase globally (see Figure II). In fact, the Intergovernmental Panel on Climate Change states with high confidence that "evapotranspiration increased by between approximately 0.5 and 1.5 mm $yr^2$ between the 1980s and early 2010s due to warming-induced increased atmospheric demand worldwide" (IPCC 2022, 568). Increases in evapotranspiration are expected to "accelerate the hydrologic cycle, altering rainfall, magnitude and timing of run-off…, [as well as] affect the soil moisture, groundwater recharge, and frequency of flood or drought, and finally groundwater level in different areas" (Kumar and Guatam 2014). Furthermore, as evapotranspiration rises, if increasing water demand is not met by higher average levels of precipitation, then there will likely be a "greater soil [moisture] deficit in summer" which is not only expected to "exacerbate impacts of heat waves as well as drought stress," but also to negatively impact agricultural productivity" (IPCC 2022, 225). In regions expected to experience a decrease in mean precipitation levels, increased evapotranspiration will further exacerbate drying (see Figures II and III). In essence, changes in climatic moisture reflect the impacts of climate change on evapotranspiration levels and mean precipitation patterns, which will interact to make "wet regions wetter and dry regions drier" (Buis 2022). This is expected to have profound effects on human activities and livelihoods, particularly in the agricultural sector.

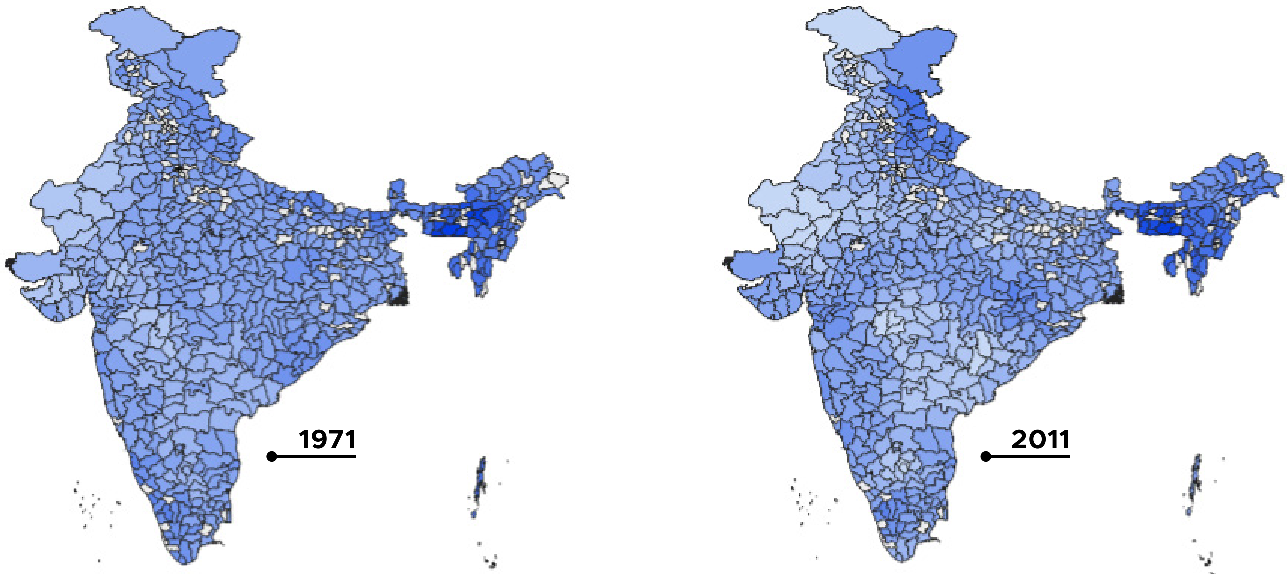
Indeed, agricultural productivity is closely tied to climatic and meteorological conditions (Kumar and Gautam 2014; Abiy et al. 2019; Gornall et al. 2010; Henderson, Storeygard, and Deichmann 2017). For example, in their 2017 study, Henderson, Storeygard, and Deichmann use a moisture index to proxy climatic conditions, arguing that because "plant growth is also a function of temperature, dividing precipitation by potential evapotranspiration, which is the appropriate non-linear function for temperature…, creates a better measure of climatic agricultural potential." It follows from the relevance of moisture for agricultural potential that changes in climatic moisture levels, resulting from climate change, will have a direct impact on changes in agricultural productivity. Essentially, as global warming continues, rising temperatures will increase evapotranspiration, impacting

**FIGURE II**
Annual Mean Potential Evapotranspiration, 1971 – 2011




*Source*: Author's calculations using data from Willmott and Feddema's Moisture Index and the 2011 Census of India. This map shows the average annual potential evapotranspiration for each district. Districts that are dark green have higher levels of potential evapotranspiration, representing higher water demand. Districts that are light green have lower levels of potential evapotranspiration, representing lower water demand. The 1971 map is displayed on the left and the 2011 map on the right. Districts in gray have no gridded observations in Willmott and Feddema's data archive.

**FIGURE III**
Annual Mean Precipitation, 1971 – 2011




*Source*: Author's calculations using data from Willmott and Feddema's Moisture Index and the 2011 Census of India. This map shows the average annual precipitation in millimeters for each district. Districts that are dark blue received more precipitation; those that are white received less precipitation. The 1971 map is displayed on the left and the 2011 map on the right. Districts in gray have no gridded observations in Willmott and Feddema's data archive.

hyrdological processes and increasing water demand for agriculture, thereby diminishing agricultural productivity if adequate adaptation measures are not implemented. Furthermore, Abiy et al. (2019) find that an "atmospheric moisture deficit at critical times of crop development causes stunting of crop development attributed to soil deficit." Climate change will not only affect agricultural productivity through its impact on growing conditions, but also its impact on the efficacy of farming systems, such as "established infrastructure, local farming practice, and individual experience" (Gornall et al. 2010). In this way, changes in mean climatic conditions, as measured by moisture, have profound effects on agricultural productivity. Finally, because climatic moisture is calculated as an annual average using spatially interpolated meteorological data, the statistic is largely unaffected by agricultural practices and urbanization, limiting endogeneity concerns. Willmott and Feddema's climatic moisture measure is estimated from meteorological data using a data-interpolation strategy based on "the spherical version of Shepard's algorithm, which employs an enhanced distance-weighting method (Shepard, 1968; Willmott et al. 1985)" (Willmott and Matsuura 2018b). Furthermore, "the number of nearby [weather] stations that influenced a grid-node estimate was increased to an average of 20, from an average of 7..., [resulting in] smaller cross-validation errors" (ibid.).[10] Willmott and Feddema's Moisture Index uses these interpolations to estimate potential evapotranspiration, rather than directly observing actual evapotranspiration. The advantage of this approach is that the moisture measure is not impacted by local agricultural practices or urbanization, mitigating issues caused by reverse causality. For example, in theory, regions with low agricultural productivity may lack the capacity to invest in irrigation systems, resulting in decreased evapotranspiration and lower near-surface atmospheric moisture (Zhang et al. 2019); similar processes may occur in urban areas, which are vulnerable to the urban "heat island" effect. However, these sources of endogeneity are mitigated through robust estimation of potential evapotranspiration as opposed to direct observation of evapotranspiration. Furthermore, substantial variation in moisture changes, particularly across the Indian subcontinent, provide a good source of heterogeneity (see Figure I and Figure IV). Overall, as measured by Willmott and Feddema's Moisture Index, moisture provides a pertinent, exogenous, and heterogeneous proxy for slow-onset climatic changes.

### 3.2 DATA

To estimate the relationships between changes in climatic moisture, urbanization, and urban growth, this study combines data from three sources: the 2011 Census of India,[11] the Willmott and Feddema Moisture Index Gridded Dataset, and the European Commission Emissions Database for Global Atmospheric Research.

As part of the 2011 Census of India, the Office of the Registrar General and Census Commissioner published statistics on the "adjusted population figures for the twelve censuses from 1901 to 2011 for India, States, Union Territories, and Districts according to [2011] jurisdictions" (Census of India 2011). Accordingly, the 2011 census includes population statistics for towns and urban agglomerations dating back to 1901, as classified by 2011 standards. In theory, this would allow for the creation of a balanced panel dataset containing twelve observations at 10-year intervals between the years of 1901 and 2011 on the population of every urban area in India according to 2011 classifications. However, population statistics before 1961 are often interpolated or unavailable due to failure or inability to conduct the census in various states during early rounds. As such, this study uses population statistics from 1971 and 2011 on Class I, II, III, IV, V, and VI cities (i.e., all urban centers identified in the 2011 census) to identify urbanization patterns and city growth.[12] For cases in which cities spill into multiple districts, large urban agglomerations are broken down into subsets to ensure that the urban population of a district is not over- or under-estimated. District-level urban populations are a sum of the population of all urban centers located in the district, including urban centers that were not classified as urban areas in 1971 but were by 2011. District-level population statistics with decadal variation to 1901 are also taken from the 2011 Census of India. Because the aggregation of Class I–VI cities provides a complete measure of the urban population, rural populations are calculated by subtracting the district-level urban population from the total district population. In the city-level analysis, each urban subset is treated as a separate observation. Cleaning and combining data on all cities in India that were classified as an urban area in both 1971 and 2011 yields a balanced panel dataset of 2,222 urban areas. These statistics are used to calculate annual city growth.

Data on moisture are taken from the Willmott and Feddema Moisture Index Gridded Dataset. The methods used to calculate Willmott and Feddema's Moisture Index are outlined in Section III.A of this paper. For districts containing multiple gridded observations, the average moisture index score is calculated using 2011 shapefiles. Data on precipitation and temperature are also taken from Willmott and Feddema's gridded datasets and averaged at the district level using similar methods. Precipitation is expressed in millimeters and temperature in degrees Celsius. District-level annualized growth rates for precipitation and temperature are calculated using the same methods employed for moisture. These measures are included in the regression analysis to completely isolate the effect of moisture and ensure robustness (Henderson, Storeygard, and Deichmann 2017). For some districts, there are no gridded observations available; these districts are dropped from the analysis. Because the estimates are calculated at a constant spatial interval, it may be argued that districts are missing moisture, temperature, and precipitation observations at random. A valid counterargument is that the smaller districts which often comprise cities are systematically more likely to be missing observations compared to large rural districts. This is a limitation that should be rectified in future studies. One solution may be to impute district-level annual means by taking the average from surrounding districts; however, this estimation method is unlikely to yield a robust measure such as those calculated using Willmott and Feddema's spatial-interpolation algorithm.

The presence of industrial production is also included in the regression analysis, again following the precedent set by Henderson, Storeygard, and Deichmann (2017). These authors find that greater baseline industrial presence led to an increase in urbanization in drier districts. Although industrial presence and growth may be a consequence of low moisture, poor agricultural productivity, and urban growth, these variables are nonetheless included in various specifications of the model to ensure this potential channel is controlled. As such, industrial presence is calculated at the district level using emissions data from the European Commission Emissions Database for Global Atmospheric Research (EDGAR). EDGAR publishes raster layers containing annual sector-specific statistics on non-short and short-cycle carbon emissions, expressed in tons and calculated at the 0.1x0.1-degree level.[13] Non-short and short-cycle carbon emissions caused by power industry and manufacturing are combined to estimate total industrial presence by district for 1971 and 2011. Emissions are summed on the district level using 2011 shapefiles. Emissions data are then matched to urban centers by district. This has a variety of drawbacks. For one, industrial presence cannot be directly tied to a single urban area within the district, rather it is an aggregate measure of total district-level emissions. This may lead to over-estimation of industrial presence for separate urban areas located within the same district. However, for cases in which there are multiple observations within the same district, the individual urban subsets often belong to the same larger urban agglomeration. As such, calculating total emissions yields a more accurate measure for local industrial presence than the district-level mean. Ideally, polygons for each urban area in the 2011 census would be used to calculate emissions within the city boundaries; however, such shapefiles are not available. This should be pursued in future studies.

### 3.3 EMPIRICAL SPECIFICATION

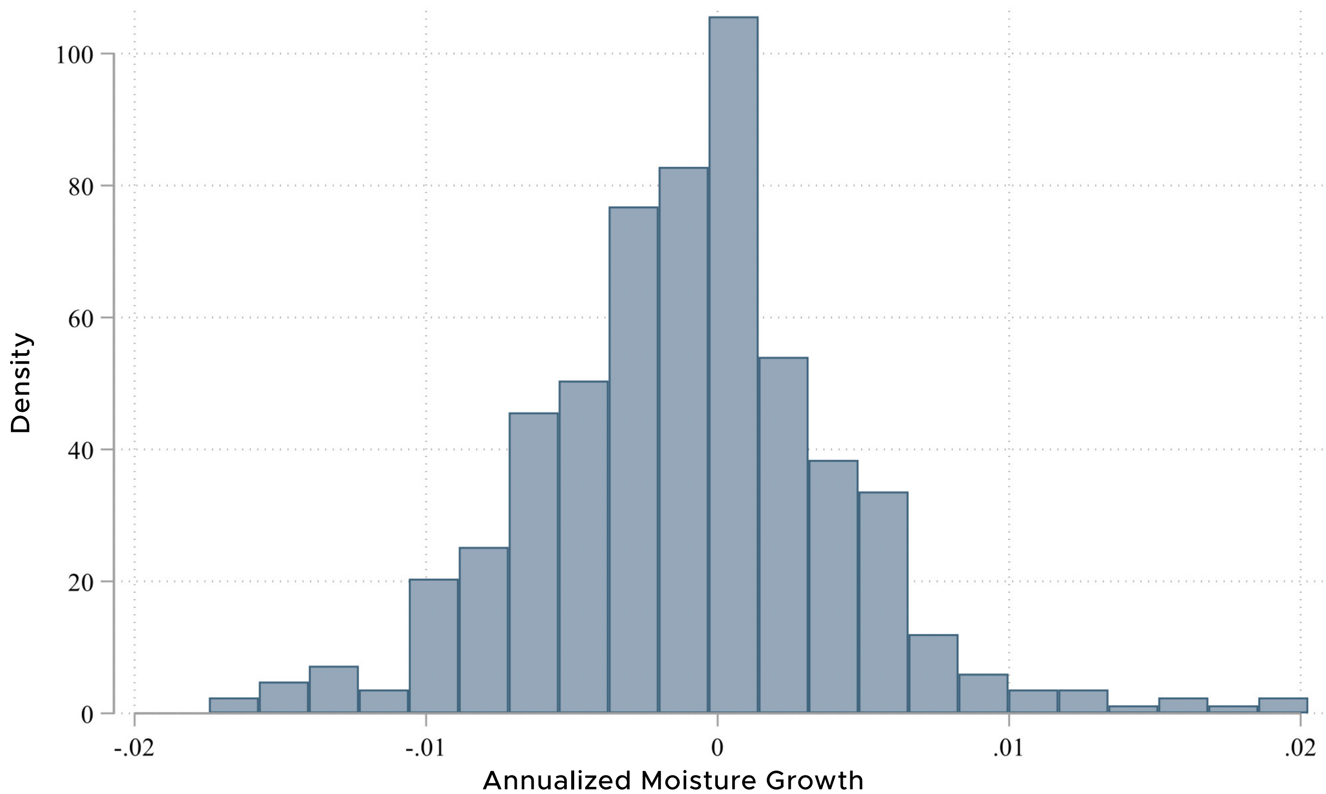
Using two panel datasets, this study estimates the effect of moisture growth on four outcomes of interest: annualized urban share growth, annualized total district-level urban population growth, annualized rural population growth, and annualized city population growth. The base specification follows:

$$Y_i = \beta_0 + \beta_1 MOISTURE\_GROWTH_i + \beta_2 X_i + \beta_3 v_i + e_i,$$

where $Y_i$ is one of the four outcomes of interest; MOISTURE_GROWTHi is the annualized moisture growth rate and the primary variable of interest; $X_i$ is a vector of controls, including baseline urban share or logged baseline urban/rural/city population, baseline moisture, and a dummy for whether the district is coastal; and $v_i$ is a vector of state fixed effects. Models that estimate the impact of moisture growth on city population growth are also clustered at the district level. Logged baseline industry emissions and annualized industry emissions growth are included as controls in the extended version of the model (columns 3, 4, and 6 in Tables I–IV). As discussed in the previous section, two additional models for each dependent variable are tested, which control for baseline average annual temperature, annualized temperature growth, baseline average annual precipitation, and annualized precipitation growth in the primary and extended models. Following the precedent set by Henderson, Storeygard, and Deichmann (2017), this is intended to serve as a robustness check for the impact of moisture on urbanization.

All dependent variables are winsorized at three

**FIGURE IV**
Distribution of Annualized Moisture Growth




*Source*: Author's calculations using Willmott and Feddema's Moisture Index data and the 2011 Census of India. This graph shows the distribution of districts experiencing moisture growth and decline from 1971–2011.

standard deviations above the mean. Results for the winsorized estimates are discussed in the following section; non-winsorized estimates are recorded in the Appendix. Results are largely consistent. Table A. I in the Appendix provides summary statistics for each of the variables used in the regressions for urban share, total urban population, and rural population. Table A. II in the appendix contains summary statistics for the city population growth regressions. Figure A. I in the Appendix shows the distribution of urban share growth; A. II the distribution of total district population growth; A. III the distribution of rural population growth; and A. IV the distribution of city population growth. Figure IV below shows the distribution of annualized moisture growth by district.

# 4 RESULTS

### 4.1 DISTRICT-LEVEL RESULTS

The results of the regression analysis using annualized growth of urban share as the dependent variable are recorded in Table I. They suggest that increased drying may contribute to increased growth in urban share. In the primary specification, the coefficient on moisture growth is significant at the 5-percent level and suggests that a 1 percentage point decrease in annualized moisture growth increases annualized urban share growth by 0.210 percentage points, all else equal. In other words, a decrease of one standard deviation in the annualized moisture growth rate increases urban share growth by 0.105 percentage points. This is consistent with the literature which finds that drying increases urbanization (Henderson, Storeygard, and Deichmann 2017). The magnitude of the coefficient on moisture growth diminishes slightly as subsequent controls are added to the regression but remains significant at the 10-percent level. The regression results also suggest that coastal districts saw greater urban share growth between 1971 and 201. In every regression specification, the results suggest that coastal districts experienced urban share growth that was 0.3 percentage points greater than non-coastal districts, significant at the 5-percent level, all else equal. This is consistent with the literature, which argues that human settlements tend to concentrate along coastlines (Neumann et al. 2014; Small and Nicholls 2003).

These findings are robust to the inclusion of controls for baseline average annual precipitation, baseline average annual temperature, precipitation growth, and temperature growth. The point estimates on moisture growth are largely unchanged and remain statistically significant at the 5-percent level. Baseline precipitation, precipitation growth and baseline temperature are all statistically insignificant in robustness checks on the primary specification and the extended specification; however, temperature growth emerges as statistically significant at the 1-percent level. The results suggest that a 1 percentage point increase in annualized average temperature growth increases urban share growth by 0.160 percentage points, all else equal. Regression results for non-winsorized urban share growth are recorded in Table A. III in the Appendix. The point estimates on moisture growth are comparable to those in the winsorized regressions and statistically significant at the 5-percent level. All other findings are generally consistent.

Looking a bit deeper into the dynamics underpinning this increase in urban share growth yields intriguing results. The point estimate on moisture growth is statistically insignificant in every regression on total urban population growth, except for the model that does not include state fixed effects. Nonetheless, the negative coefficient on moisture in each of these regressions suggests that total urban population may increase more rapidly in drying districts; however, statistical insignificance renders this finding largely irrelevant. Instead, what emerges as statistically significant for urban population growth is coastal location, high baseline industrial presence, industrial growth, and positive temperature growth. The most marked difference between the findings on urban share growth and total urban population growth pertains to the importance of baseline industrial presence and growth. The findings suggest that higher baseline industrial presence and industrial growth increases total urban population growth, all else equal. Coastal location – and, in robustness checks, temperature growth  has a similar effect on total urban population growth when compared to urbanization growth.

The results of the regression analysis using rural population as the dependent variable are more interesting. The point estimate on moisture growth is positive and statistically significant in all regression specifications. In the primary specification, moisture growth is significant at the 5-percent level, and the results suggest that a 1 percentage point increase in moisture growth increases rural population growth by 0.130 percentage points, all else equal. In other words, a one standard deviation decrease in moisture growth decreases rural population growth by 0.065

### TABLE I: Regression Results: Urban Share Growth, Winsorized

| Independent Variable | (1) | (2) | (3) | (4) | (5) | (6) |
|---|---|---|---|---|---|---|
| Baseline urban share | -0.029***<br>(0.003) | -0.031***<br>(0.003) | -0.032***<br>(0.003) | -0.032***<br>(0.003) | -0.032***<br>(0.003) | -0.033***<br>(0.003) |
| Baseline moisture | 0.003***<br>(0.001) | 0.002<br>(0.002) | 0.002<br>(0.002) | 0.002<br>(0.002) | 0.002<br>(0.002) | 0.002<br>(0.002) |
| Coastal | 0.006***<br>(0.001) | 0.003**<br>(0.001) | 0.003**<br>(0.001) | 0.003**<br>(0.001) | 0.003**<br>(0.001) | 0.003**<br>(0.001) |
| Annualized moisture growth | -0.035<br>(0.086) | -0.210**<br>(0.103) | -0.220**<br>(0.103) | -0.202**<br>(0.103) | -0.217**<br>(0.103) | -0.211**<br>(0.104) |
| Baseline industry emissions | - | - | 0.0006<br>(0.0005) | 0.0006<br>(0.0006) | - | 0.0005<br>(0.0006) |
| Annualized industry emissions growth | - | - | - | 0.008<br>(0.023) | - | 0.014<br>(0.023) |
| Baseline precipitation | - | - | - | - | 0.00001<br>(0.00001) | 0.00001<br>(0.00001) |
| Annualized precipitation growth | - | - | - | - | -0.024<br>(0.037) | -0.026<br>(0.037) |
| Baseline air temperature | - | - | - | - | 0.001<br>(0.001) | 0.001<br>(0.001) |
| Annualized air temperature growth | - | - | - | - | 0.160***<br>(0.048) | 0.159***<br>(0.048) |
| State fixed effects | NO | YES | YES | YES | YES | YES |
| Constant | 0.015***<br>(0.001) | 0.016***<br>(0.002) | 0.027***<br>(0.009) | 0.026**<br>(0.010) | 0.016***<br>(0.002) | 0.024***<br>(0.010) |
| Adjusted R-Squared | 0.200 | 0.336 | 0.337 | 0.336 | 0.350 | 0.350 |

* $p < 0.010$, ** $p < 0.05$, *** $p < 0.01$. Notes: This table regresses moisture growth and various additional controls (listed in the leftmost column) on annualized urban share growth. The dependent variable is winsorized to three standard deviations outside the mean. Regressions 2–6 employ state fixed effects. Urban share is calculated by dividing urban population over total district population.

### TABLE II: Regression Results: Total Urban Population Growth, Winsorized

| Independent Variable | (1) | (2) | (3) | (4) | (5) | (6) |
|---|---|---|---|---|---|---|
| Log(Baseline urban population) | -0.004***<br>(0.0004) | -0.004***<br>(0.0004) | -0.005***<br>(0.0005) | -0.005***<br>(0.0005) | -0.004***<br>(0.0004) | -0.005***<br>(0.0005) |
| Baseline moisture | -0.0004<br>(0.001) | -0.0008<br>(0.002) | -0.001<br>(0.002) | -0.002<br>(0.002) | -0.0008<br>(0.002) | -0.002<br>(0.002) |
| Coastal | 0.004**<br>(0.001) | 0.004**<br>(0.002) | 0.004**<br>(0.002) | 0.004**<br>(0.002) | 0.004***<br>(0.002) | 0.004**<br>(0.002) |
| Annualized moisture growth | -0.178*<br>(0.097) | -0.105<br>(0.120) | -0.070<br>(0.117) | -0.073<br>(0.117) | -0.110<br>(0.121) | -0.084<br>(0.118) |
| Baseline industry emissions | - | - | 0.004***<br>(0.0007) | 0.003***<br>(0.0007) | - | 0.003***<br>(0.0007) |
| Annualized industry emissions growth | - | - | - | 0.043*<br>(0.026) | - | 0.047*<br>(0.026) |
| Baseline precipitation | - | - | - | - | 0.00001<br>(0.00001) | 0.00002<br>(0.00002) |
| Annualized precipitation growth | - | - | - | - | -0.003<br>(0.043) | -0.004<br>(0.042) |
| Baseline air temperature | - | - | - | - | 0.001<br>(0.001) | 0.001<br>(0.001) |
| Annualized air temperature growth | - | - | - | - | 0.168***<br>(0.056) | 0.154***<br>(0.054) |
| State fixed effects | NO | YES | YES | YES | YES | YES |
| Constant | 0.074***<br>(0.005) | 0.075***<br>(0.006) | 0.152***<br>(0.016) | 0.144***<br>(0.017) | 0.075***<br>(0.006) | 0.140***<br>(0.017) |
| Adjusted R-Squared | 0.175 | 0.275 | 0.313 | 0.315 | 0.282 | 0.321 |

* $p < 0.010$, ** $p < 0.05$, *** $p < 0.01$. Notes: This table regresses moisture growth and various additional controls (listed in the leftmost column) on annualized total district-level urban population growth. The dependent variable is winsorized to three standard deviations outside the mean. Regressions 2–6 employ state fixed effects. Urban population is calculated as the sum of the population of Class I–VI cities located within a district.

**TABLE III: Regression Results: Rural Population Growth, Winsorized**

| Independent Variable | (1) | (2) | (3) | (4) | (5) | (6) |
|---|---|---|---|---|---|---|
| Baseline rural population | -0.002*** | -0.0009** | -0.0003 | 0.0003 | -0.0009** | 0.0003 |
| | (0.0003) | (0.0004) | (0.0005) | (0.0005) | (0.0004) | (0.0005) |
| Baseline moisture | -0.001* | -0.002*** | -0.002*** | -0.002*** | -0.002** | -0.002** |
| | (0.0008) | (0.0009) | (0.0009) | (0.0009) | (0.0009) | (0.0009) |
| Coastal | -0.007*** | -0.002*** | -0.002*** | -0.002*** | -0.002*** | -0.002*** |
| | (0.0008) | (0.0007) | (0.0007) | (0.0007) | (0.0007) | (0.0007) |
| Annualized moisture growth | -0.155*** | 0.130** | 0.130** | 0.131** | 0.143*** | 0.143*** |
| | (0.057) | (0.051) | (0.051) | (0.050) | (0.051) | (0.050) |
| Log(Baseline industry emissions) | - | - | -0.0006* | -0.001*** | - | -0.001*** |
| | | | (0.0003) | (0.0003) | | (0.0003) |
| Annualized industry emissions growth | - | - | - | 0.043*** | - | 0.042*** |
| | | | | (0.011) | | (0.011) |
| Baseline precipitation | - | - | - | - | -9.54e-06 | -9.48e-06 |
| | | | | | (6.84e-06) | (6.73e-06) |
| Annualized precipitation growth | - | - | - | - | 0.005 | -0.0006 |
| | | | | | (0.018) | (0.018) |
| Baseline air temperature | - | - | - | - | -0.0006 | -0.0004 |
| | | | | | (0.0005) | (0.0005) |
| Annualized air temperature growth | - | - | - | - | -0.049** | -0.036 |
| | | | | | (0.023) | (0.023) |
| State fixed effects | NO | YES | YES | YES | YES | YES |
| Constant | 0.042*** | 0.031** | 0.013 | -0.005 | 0.031*** | -0.004 |
| | (0.005) | (0.006) | (0.011) | (0.012) | (0.006) | (0.012) |
| Adjusted R-Squared | 0.2141 | 0.609 | 0.611 | 0.623 | 0.615 | 0.627 |

* p < 0.010, ** p < 0.05, *** p < 0.01. Notes: This table regresses moisture growth and various additional controls (listed in the leftmost column) on annualized total district-level rural population growth. The dependent variable is winsorized to three standard deviations outside the mean. Regressions 2–6 employ state fixed effects. Rural population is calculated as the difference between total population and the sum of the population of Class I–VI cities located within a district.

percentage points. The point estimate on moisture is significant at the 1-percent level after controlling for temperature and precipitation, and the magnitude is slightly larger. The other variables that emerge as consistently statistically significant for rural population growth are inland location, lower baseline moisture – perhaps because such regions are now experiencing increases in moisture – low baseline industrial emissions, and industrial growth. Taken together, these results offer weak evidence that drier conditions increase total urban population growth but strong evidence that drying decreases rural population growth. Instead, districts with increased moisture experience faster rural growth. This may underlie the apparent increase in urban share in drying districts.

### 4.2 CITY-LEVEL RESULTS

The results of the regression analysis using annualized city population growth as the dependent variable are recorded in Table IV. The point estimate for moisture growth is significant at the 1-percent level in all specifications that include state fixed effects. In the primary specification, the point estimate on moisture growth suggests that a 1 percentage point increase in moisture growth leads to a 0.373 percentage point increase in city population growth, all else equal. In other words, a one standard deviation increase in moisture growth in the surrounding district leads to a 0.187 percentage point increase in city population growth. The point estimate declines slightly as subsequent controls are added and more sharply after the inclusion of temperature and precipitation controls, down to 0.329; however, the coefficient remains statistically significant at the 1-percent level. These results suggest that established cities (i.e., cities that existed at baseline) grew more quickly in districts that experienced an increase in moisture. This finding is in line with the literature on agricultural productivity improvements contributing to urban growth. Baseline industry emissions, annualized industry emissions growth, baseline temperature, and annualized temperature growth also emerge as statistically significant for city population growth. Of

**TABLE IV: Regression Results: Urban Population Growth by Urban Center, Winsorized**

| Independent Variable | (1) | (2) | (3) | (4) | (5) | (6) |
|---|---|---|---|---|---|---|
| Log(Baseline urban population) | 0.0005<br>(0.0005) | 0.0006<br>(0.0005) | 0.0006<br>(0.0005) | 0.0006<br>(0.0005) | 0.0006<br>(0.0005) | 0.0006<br>(0.0005) |
| Baseline moisture | 0.002<br>(0.001) | 0.0004<br>(0.002) | 0.0003<br>(0.002) | 0.0003<br>(0.002) | 0.0002<br>(0.002) | -0.0001<br>(0.002) |
| Coastal | -0.002<br>(0.002) | 0.002<br>(0.002) | 0.002<br>(0.002) | 0.001<br>(0.002) | 0.002<br>(0.002) | 0.002<br>(0.002) |
| Annualized moisture growth | 0.082<br>(0.095) | 0.373***<br>(0.131) | 0.371***<br>(0.132) | 0.370***<br>(0.134) | 0.334***<br>(0.133) | 0.329**<br>(0.136) |
| Baseline industry emissions | - | - | -0.0007<br>(0.0005) | -0.001***<br>(0.0005) | - | -0.001*<br>(0.0005) |
| Annualized industry emissions growth | - | - | - | 0.058***<br>(0.022) | - | 0.059***<br>(0.022) |
| Baseline precipitation | - | - | - | - | -5.17e-06<br>(0.00001) | -1.10e-06<br>(0.00001) |
| Annualized precipitation growth | - | - | - | - | 0.028<br>(0.029) | 0.023<br>(0.029) |
| Baseline air temperature | - | - | - | - | 0.001**<br>(0.0007) | 0.002**<br>(0.0007) |
| Annualized air temperature growth | - | - | - | - | 0.070<br>(0.045) | 0.081*<br>(0.046) |
| State fixed effects | NO | YES | YES | YES | YES | YES |
| Constant | 0.018***<br>(0.005) | 0.017***<br>(0.006) | 0.005**<br>(0.011) | -0.006<br>(0.011) | 0.017***<br>(0.006) | -0.007<br>(0.011) |
| Adjusted R-Squared | 0.007 | 0.108 | 0.110 | 0.116 | 0.109 | 0.118 |

* p < 0.010, ** p < 0.05, *** p < 0.01. Notes: This table regresses moisture growth and various additional controls (listed in the leftmost column) on annualized city population growth. The dependent variable is winsorized to three standard deviations outside the mean. Regressions 2–6 employ state fixed effects. All regressions cluster standard errors at the district level.

these variables, industry growth has the strongest statistical significance. The magnitude of the point estimate suggests that a 1 percentage point increase in district industry growth leads to a 0.058 increase in city growth. Non-winsorized regression results are displayed in Table A. IV in the Appendix. The findings are consistent across both winsorized and non-winsorized estimates.

# 5 DISCUSSION

This study finds that drying increases urban share growth in districts across India. This is broadly in line with the literature on climate change acting as a "push" factor contributing to increased urbanization (Henderson, Storeygard, and Deichmann 2017; Barrios, Bertinelli, and Strobl 2006). However, the results of this study also suggest that moisture growth does not have a statistically significant effect on total district urban population growth. Instead, drying contributes to slower rural population growth; conversely, moisture increase contributes to more rapid rural population growth. This has interesting implications for the findings on urban share growth, suggesting that the observed increase in urbanization may be driven by stifled rural growth and/or rural out-migration rather than by urban population growth. Rural residents may simply be relocating to areas with more favorable farming conditions rather than to nearby urban areas; this may also contribute to the observed increase in rural population growth in districts experiencing moisture increase.

Indeed, a recent report by the World Bank finds that the "southern Indian highlands… will be climate in-migration hotspots" while the "northern part of the Gangetic Plain, and the corridor from Delhi to Lahore" and the "irrigated areas and rice-growing areas are likely to see population dampening as a result of out-migration" (Rigaud et al. 2018, 89). A rough comparison between the moisture map displayed in Figure I and a map from the National Aeronautics and Space Administration's Socioeconomic Data and Applications Center (SEDAC) database showing internal migration flows across India (Figure A. V in the Appendix) provides support for the argument that individuals may be moving out of drying districts and into districts more conducive to agriculture. In this way, drying districts may be urbanizing more rapidly than districts experiencing moisture gains, though rural out-migration likely plays a particularly important role in this transition.

This study also finds evidence that cities in districts experiencing increases in climatic moisture tend to grow faster than cities located in drying regions. Together with the results on rural population dynamics, these findings suggest that increased moisture – and thus improvements to agricultural productivity – may contribute to rural growth, which subsequently results in gains to nearby urban centers. This is in line with the literature, which suggests urban growth may be augmented by local gains to agricultural productivity (Asher et al. 2022; Bustos, Garber, and Ponticelli 2019). However, it is important to reconcile this finding with the district-level regression analysis, which finds that moisture has no impact on total urban population growth. As previously noted, the city-level analysis employs a panel dataset of urban centers and does not account for cities that emerged or were reclassified between 1971 and 2011.[14] While "established" urban centers experienced more rapid growth in moister districts, it may be that rural villages coalesced into small census towns in drying districts as individuals sought off-farm employment to escape declining agricultural conditions.[15]

The emergence of new towns may explain why population growth in "established" cities does not correspond with significantly higher total urban population growth in moister districts as compared to drier districts. In essence, climate change may hasten two types of urbanization: (i) the rise of small census towns, which result from increased demand for off-farm employment but ultimately stagnate due to rural out-migration; and (ii) rapid, sustained urban center growth driven by improvements to agricultural productivity. Additional analysis is necessary to confirm or refute this theory, though scholars have become increasingly interested in India's small and dispersed "emergent urban areas" (Jan van Duijne and Nijman 2019). The role of reclassification is also an understudied and important phenomenon, particularly in India, where it is estimated that reclassification may have contributed to almost 9.6 percent of measured urban growth (Menashe-Oren and Bocquier 2021).

Additionally, future studies should further explore the nuanced relationships between climate change, migration, and urbanization. One of the major drawbacks of this study is that migration and the motivations for migration are not directly observed. Furthermore, this study focuses primarily on local, intra-district migration as opposed to cross-district, cross-state, and international migration; most Indian districts are small geographic units, so changes in climatic conditions are likely to induce cross-district or cross-state migration. Future studies should also explore how moisture conditions, urbanization levels, and industrial presence in neighboring districts affect intra-district dynamics. Similarly, fertility and mortality trends are not directly observed in this study. Both migration and natural demographic trends play an important role in urbanization and urban population growth (Menashe-Oren and Bocquier 2021); because these processes are intricately intertwined, this study does not explicitly distinguish between the two but considers overall population and demographic changes. However, because there are important and distinct policy implications for addressing different types of migration, as well as natural demographic trends, future studies should seek to disentangle the dynamics of these phenomena and their impacts on urbanization and urban growth.

Another drawback of this study is that agricultural output is not directly measured. As more accurate, systematic data on crop yields across India become available, future studies should seek to establish more robust causal relationships between climatic changes, agricultural yields, migration, and urbanization. However, future studies should not only consider the impact of long-term, slow-onset climatic changes, but also shifts in the seasonal variation of rainfall patterns and extreme weather events, as both directly impact agricultural yields. Climatic and meteorological conditions immediately before and during the growing season may have particularly poignant effects on output and thus more directly influence decisions to migrate. Similarly, extreme weather events – such as intense rains, floods, heatwaves, and droughts – not only have the potential to destroy crop yields, but also to directly induce migration as households flee devastation. Nonetheless, future studies should be aware of endogeneity concerns, particularly if governments introduce targeted legislation to improve conditions for households in climate-affected areas, to stem the flow of migration, or to induce urbanization patterns.[16]

# 6 CONCLUSION

Overall, this study finds that residents in drying districts may become increasingly concentrated in urban areas, but the highest population pressures may be found in districts experiencing an increase in climatic moisture. This finding has important implications for urban planning and climate resilience efforts throughout India. For one, residents in burgeoning towns must have access to the infrastructure and services necessary to help parlay the growth of off-farm employment into structural transformation.[17] Promoting the growth of smaller urban areas will not only lead to economic growth in rural districts, but also help support those who stand to be most severely impacted by climate change. Furthermore, creating more local opportunities for off-farm and industrial employment through the sustainable growth of towns may help towns absorb rural residents who would otherwise move to areas with better agricultural land, thus helping relieve pressure on in-demand regions. Mitra and Tripathi (2021) explain: "The proper management of new census towns will play a pivotal role in the context of higher and balanced urbanization…, [which] will help reduce pressure on large cities and the impact of the other diseconomies." Harnessing the potential of growing towns and small cities will be a crucial challenge for both India's urban development and climate change adaptation efforts.

Additionally, districts in areas experiencing moisture growth need to be ready to accommodate significant population increases. Rapid urban expansion in major cities across India has already put significant strain on municipal authorities. In a World Bank report, Ellis and Roberts (2016) find that "South Asia's cities are not fulfilling their development potential as characterized by either prosperity or livability because of the congestion pressures that growing populations are exerting on infrastructure, basic services, land, housing, and the environment" (77). Lofty policy solutions such as strengthening urban governance, increasing infrastructure investment, or implementing climate-conscious urban expansion plans need to be tailored to address local needs and capacities. Climate change and urbanization pose highly localized challenges that require highly localized solutions. As such, future research should consider how these processes will manifest in specific, meso-level settings.

Understanding how climate change and urbanization converge will help inform more effective, integrated policy responses to address two of the most formidable challenges facing our world in the decades to come. The evidence presented in this study suggests that changing climatic conditions will have a significant impact on urbanization patterns, whereby populations in drying regions become increasingly ossified into small towns while population pressures in both cities and rural areas increase in regions experiencing greater climatic moisture. Policies to support urbanization efforts should take these dynamics into account when planning for future development, otherwise the challenges posed by urban growth and climate change may compound one another and prove too heavy for local, national, and international governments to bear. On the other hand, sustainable urbanization has the potential to support human flourishing at all levels and insulate against the impacts of climate change. Indeed, as climate change continues to transform our environment and impact livelihoods, safe and sustainable urban development will be an integral part of creating a prosperous world for all.

# APPENDIX

**TABLE A. I. District-Level Descriptive Statistics**

| Independent Variable | Mean | SD | Minimum | Maximum |
|---|---|---|---|---|
| Urban share (2011) | 0.246 | 0.175 | 0.035 | 0.981 |
| Urban share (1971) | 0.153 | 0.129 | 0.008 | 0.906 |
| Annualized urban share growth | 0.014 | 0.010 | -0.007 | 0.044 |
| Urban population (2011) | 609,538 | 905,518 | 4,644 | 8,760,511 |
| Urban population (1971) | 167,302 | 229,865 | 331 | 2,074,354 |
| Annualized urban population growth | 0.034 | 0.011 | 0.008 | 0.068 |
| Rural population (2011) | 1,523,144 | 1,004,746 | 23,610 | 6,074,188 |
| Rural population (1971) | 804,629 | 520,695 | 12,683 | 3,362,126 |
| Annualized rural population growth | 0.016 | 0.006 | -0.004 | 0.037 |
| Baseline moisture | 0.913 | 0.405 | 0.069 | 1.9000 |
| Annualized moisture growth | -0.001 | 0.005 | -0.018 | 0.020 |
| Baseline industry emissions | 1.53e-07 | 2.16e-07 | 7.54e-10 | 1.93e-06 |
| Annualized industry emissions growth | 0.036 | 0.018 | -0.032 | 0.108 |
| Annualized district population growth | 0.020 | 0.006 | 0.003 | 0.057 |
| Baseline average annual precipitation | 48.497 | 45.439 | 11.868 | 716.508 |
| Annualized precipitation growth | -0.006 | 0.012 | -0.044 | 0.025 |
| Baseline average annual temperature | 0.944 | 0.729 | 0.304 | 7.725 |
| Annualized temperature growth | -0.007 | 0.011 | -0.048 | 0.022 |

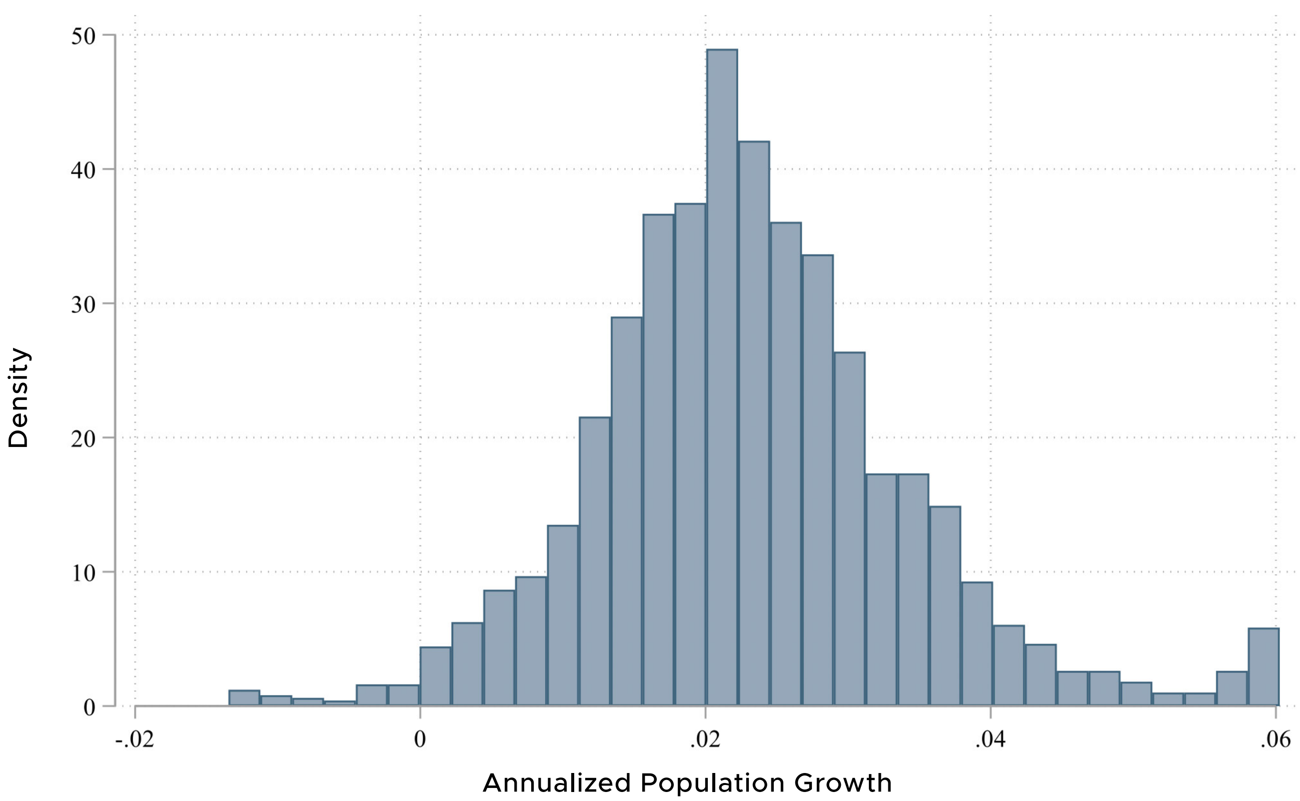
Notes: This table displays the summary statistics for variables used in the urban share growth, total district urban population growth, and rural population growth regressions. The variable name is displayed in the leftmost column. Column 2 displays the mean; Column 3 displays the standard deviation; Column 4 displays the minimum value the variable takes; and Column 5 displays the maximum value. Annualized urban share, urban population, and rural population growth rates reflect winsorization.

**TABLE A. II. Urban Center–Level Descriptive Statistics**

| Independent Variable | Mean | SD | Minimum | Maximum |
|---|---|---|---|---|
| Urban population (2011) | 114,110 | 355,764 | 1,204 | 8,495,492 |
| Urban population (1971) | 36,730 | 91,043 | 96 | 1,750,134 |
| Annualized urban population growth | 0.023 | 0.011 | -0.013 | 0.060 |
| Baseline moisture | 0.808 | 0.386 | 0.069 | 1.9 |
| Annualized moisture growth | -0.0001 | 0.005 | -0.017 | 0.020 |
| Baseline industry emissions | 2.04e-07 | 2.38e-07 | 7.54e-10 | 1.93e-06 |
| Annualized industry emissions growth | 0.038 | 0.019 | -0.032 | 0.108 |
| Baseline average annual precipitation | 42.222 | 30.408 | 11.868 | 716.508 |
| Annualized precipitation growth | -0.004 | 0.012 | -0.044 | 0.025 |
| Baseline average annual temperature | 0.868 | 0.573 | .304 | 7.725 |
| Annualized temperature growth | -0.006 | 0.011 | -0.048 | 0.022 |

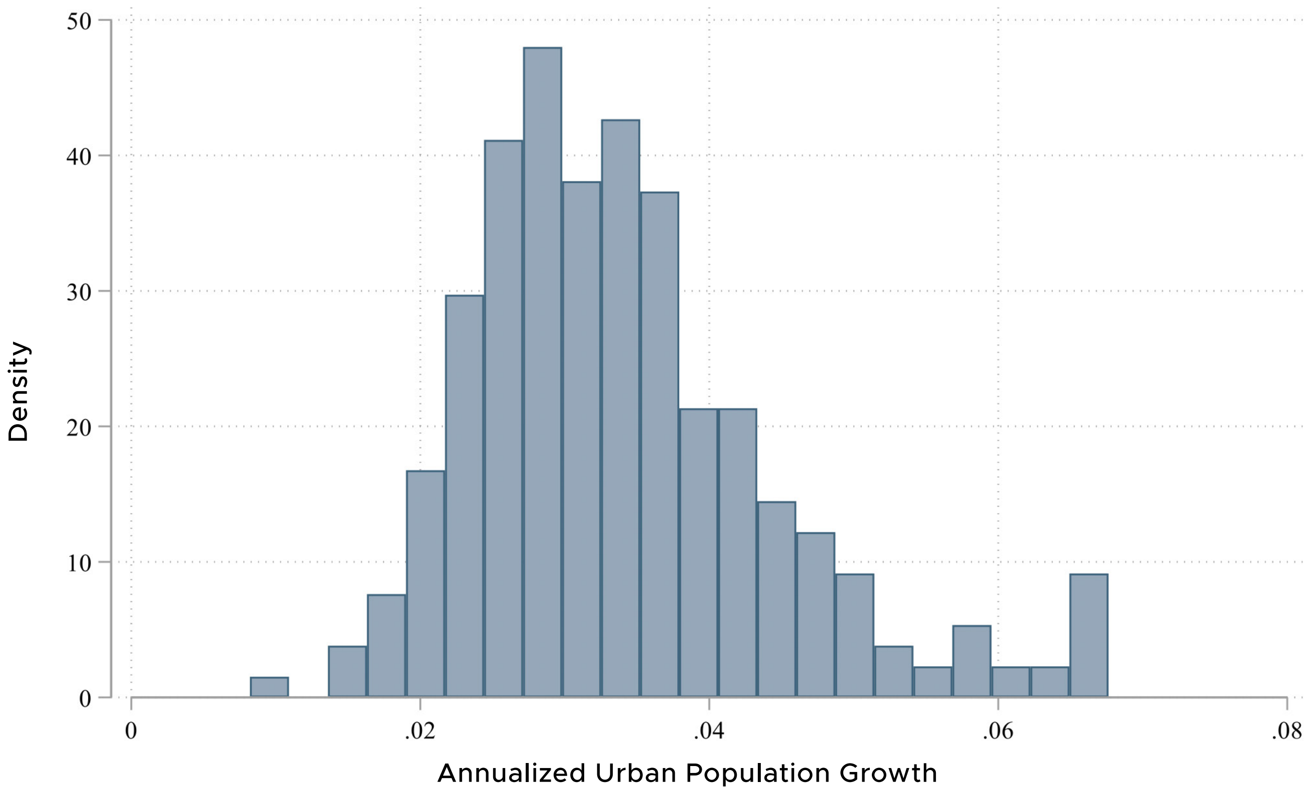
Notes: This table displays the summary statistics for variables used in the city population growth regressions. The variable name is displayed in the leftmost column. Column 2 displays the mean; Column 3 displays the standard deviation; Column 4 displays the minimum value the variable takes; and Column 5 displays the maximum value. City population growth rates reflect winsorization.

**FIGURE A. I. Distribution of Annualized Urban Share Growth**



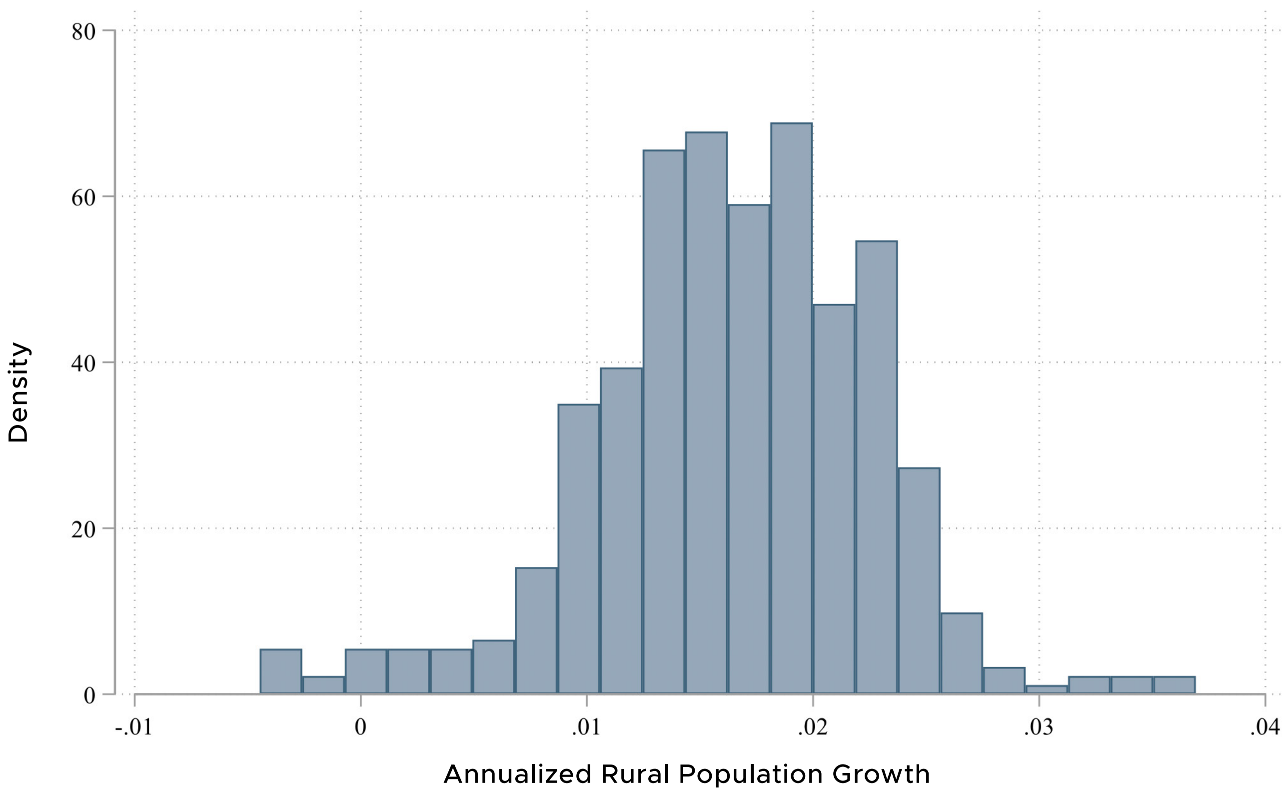

Source: Author's calculations using data from the 2011 Census of India. Graph shows distribution of annualized growth in urban share. Annualized urban share growth is winsorized to three standard deviations from the mean.

**FIGURE A. II. Distribution of Annualized Urban Population Growth**




Source: Author's calculations using data from the 2011 Census of India. This graph shows the distribution of annualized growth in total district urban population. Annualized total urban growth is winsorized to three standard deviations from the mean.

**FIGURE A. III. Distribution of Annualized Rural Population Growth**




Source: Author's calculations using data from the 2011 India Census. This graph shows the distribution of annualized growth in rural population. Annualized rural growth is winsorized to three standard deviations from the mean.

## TABLE A. III. Regression Results: Urban Share Growth, Non-winsorized

| Independent Variable | (1) | (2) | (3) | (4) | (5) | (6) |
|---|---|---|---|---|---|---|
| Baseline urban share | -0.030*** | -0.032*** | -0.033*** | -0.033*** | -0.033*** | -0.034*** |
| | (0.003) | (0.003) | (0.004) | (0.004) | (0.003) | (0.004) |
| Baseline moisture | 0.003** | 0.002 | 0.002 | 0.002 | 0.002 | 0.001 |
| | (0.001) | (0.002) | (0.002) | (0.002) | (0.002) | (0.002) |
| Coastal | 0.006*** | 0.004** | 0.003** | 0.003** | 0.004*** | 0.004** |
| | (0.001) | (0.002) | (0.002) | (.002) | (0.002) | (0.002) |
| Annualized moisture growth | -0.040 | -0.212** | -0.204* | -0.205* | -0.220** | -0.214** |
| | (0.090) | (0.109) | (0.109) | (0.109) | (0.120) | (0.120) |
| Log(Baseline industry emissions) | - | - | 0.0006 | 0.0006 | - | 0.0005 |
| | | | (0.0006) | (0.0006) | | (0.0006) |
| Annualized industry emissions growth | - | - | - | 0.006 | - | 0.012 |
| | | | | (0.024) | | (0.024) |
| Baseline precipitation | - | - | - | - | 0.00001 | 0.00001 |
| | | | | | (0.00001) | (0.00001) |
| Annualized precipitation growth | - | - | - | - | -0.022 | -0.024 |
| | | | | | (0.039) | (0.039) |
| Baseline air temperature | - | - | - | - | 0.001 | 0.001 |
| | | | | | (0.001) | (0.001) |
| Annualized air temperature growth | - | - | - | - | 0.162*** | 0.162*** |
| | | | | | (0.050) | (0.051) |
| State fixed effects | NO | YES | YES | YES | YES | YES |
| Constant | 0.015*** | 0.017*** | 0.027** | 0.026*** | 0.016*** | 0.024** |
| | (0.001) | (0.002) | (0.010) | (0.010) | (0.002) | (0.010) |
| Adjusted R-Squared | 0.195 | 0.320 | 0.320 | 0.319 | 0.333 | 0.331 |

* p < 0.010, ** p < 0.05, *** p < 0.01. Notes: This table regresses moisture growth and various additional controls (listed in the leftmost column) on annualized urban share growth. Regressions 2–6 employ state fixed effects. Urban share is calculated by dividing urban population over total district population.

## TABLE A. IV. Regression Results: Urban Population Growth, Non-winsorized

| Independent Variable | (1) | (2) | (3) | (4) | (5) | (6) |
|---|---|---|---|---|---|---|
| Log(Baseline urban population) | -0.004*** | -0.004*** | -0.005*** | -0.005*** | -0.004*** | -0.005*** |
| | (0.0004) | (0.0005) | (0.0005) | (0.0005) | (0.0005) | (0.0005) |
| Baseline moisture | -0.0007 | -0.001 | -0.002 | -0.002 | -0.001 | -0.002 |
| | (0.001) | (0.002) | (0.002) | (0.002) | (0.002) | (0.002) |
| Coastal | 0.004** | 0.004** | 0.004** | 0.004** | 0.005*** | 0.004** |
| | (0.002) | (0.002) | (0.002) | (0.002) | (0.002) | (0.002) |
| Annualized moisture growth | -0.190* | -0.108 | -0.072 | -0.076 | -0.114 | -0.086 |
| | (0.100) | (0.124) | (0.121) | (0.121) | (0.125) | (0.122) |
| Log(Baseline industry emissions) | - | - | 0.004*** | 0.003*** | - | 0.003*** |
| | | | (0.0007) | (0.0008) | | (0.0008) |
| Annualized industry emissions growth | - | - | - | 0.041 | - | 0.046* |
| | | | | (0.027) | | (0.026) |
| Baseline precipitation | - | - | - | - | 0.00001 | 0.00002 |
| | | | | | (0.00002) | (0.00002) |
| Annualized precipitation growth | - | - | - | - | -0.004 | -0.006 |
| | | | | | (0.044) | (0.043) |
| Baseline air temperature | - | - | - | - | 0.001 | 0.001 |
| | | | | | (0.001) | (0.001) |
| Annualized air temperature growth | - | - | - | - | 0.176*** | 0.161*** |
| | | | | | (0.058) | (0.056) |
| State fixed effects | NO | YES | YES | YES | YES | YES |
| Constant | 0.076*** | 0.078*** | 0.157*** | 0.149*** | 0.077*** | 0.144*** |
| | (0.005) | (0.006) | (0.016) | (0.017) | (0.006) | (0.017) |
| Adjusted R-Squared | 0.173 | 0.269 | 0.307 | 0.310 | 0.277 | 0.316 |

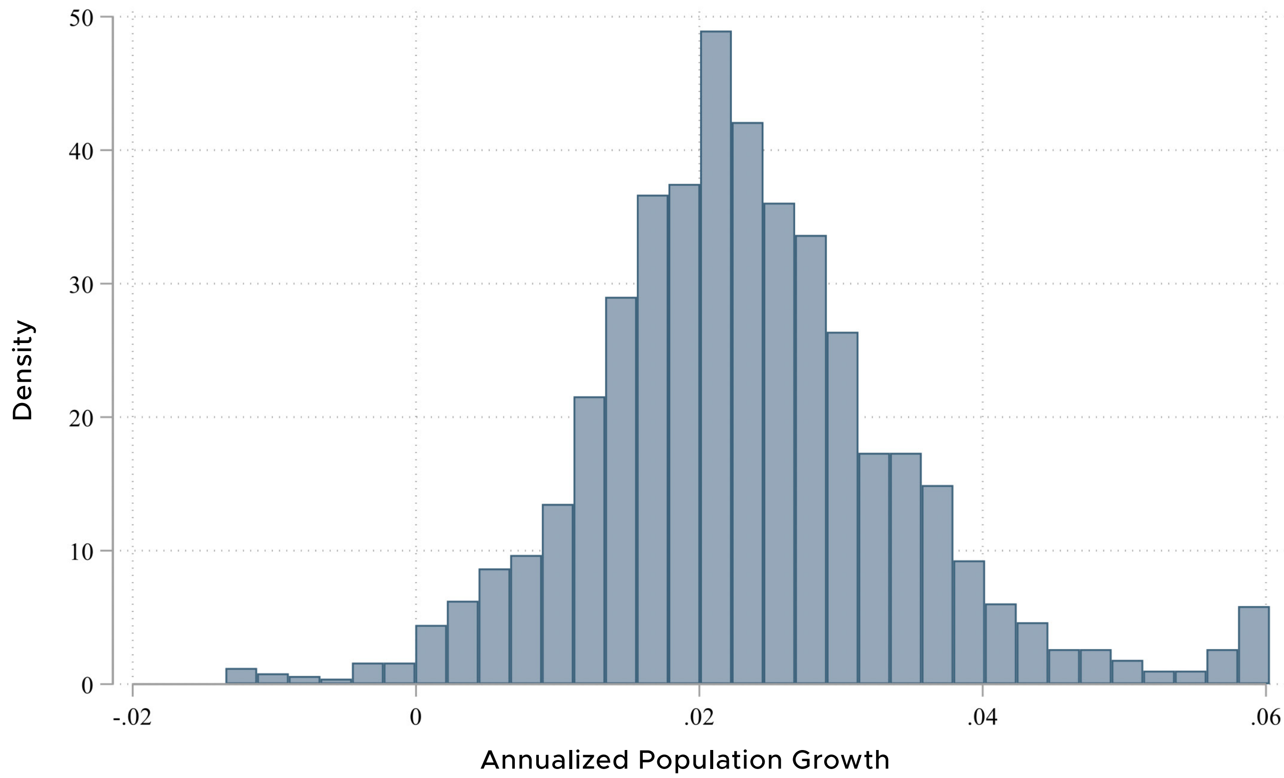
* p < 0.010, ** p < 0.05, *** p < 0.01. Notes: This table regresses moisture growth and various additional controls (listed in the leftmost column) on annualized urban population growth. Regressions 2–6 employ state fixed effects. Urban population is calculated as the sum of the population of Class I–VI cities located within a district.

## TABLE A. V. Regression Results: Rural Population Growth, Non-winsorized

| Independent Variable | (1) | (2) | (3) | (4) | (5) | (6) |
|---|---|---|---|---|---|---|
| Baseline rural population | -1.66e-09*** | -6.15e-10 | 3.39e-10 | 9.29e-10 | -6.61e-10 | 8.51e-10 |
| | (6.01e-10) | (5.39e-10) | (9.17e-10) | (9.91e-10) | (5.25e-10) | (8.86e-10) |
| Baseline moisture | -0.0006 | -0.002* | -0.002* | -0.002* | -0.002 | -0.002 |
| | (0.0008) | (0.001) | (0.001) | (0.001) | (0.001) | (0.001) |
| Coastal | -0.008*** | -0.003*** | -0.003*** | -0.003*** | -0.003*** | -0.003*** |
| | (0.001) | (0.0009) | (0.0009) | (0.0009) | (0.0009) | (0.0009) |
| Annualized moisture growth | -0.116 | 0.134* | 0.133* | 0.133** | 0.152** | 0.151*** |
| | (0.072) | (0.072) | (0.071) | (0.068) | (0.063) | (0.060) |
| Baseline industry emissions | | | -0.0008 | -0.001** | | -0.001** |
| | | | (0.0006) | (0.0007) | | (0.0006) |
| Annualized industry emissions growth | | | | 0.050*** | | 0.047*** |
| | | | | (0.015) | | (0.014) |
| Baseline precipitation | | | | | -9.71e-06 | -9.00e-06 |
| | | | | | (0.00001) | (0.00001) |
| Annualized precipitation growth | | | | | 0.018 | 0.012 |
| | | | | | (0.027) | (0.027) |
| Baseline air temperature | | | | | -0.001 | -0.001 |
| | | | | | (0.002) | (0.002) |
| Annualized air temperature growth | | | | | -0.058 | -0.049 |
| | | | | | (0.038) | (0.036) |
| State fixed effects | NO | YES | YES | YES | YES | YES |
| Constant | 0.019*** | 0.019*** | 0.005 | -0.006 | 0.020*** | -0.004 |
| | (0.001) | (0.001) | (0.011) | (0.012) | (0.001) | (0.011) |
| Adjusted R-Squared | 0.179 | 0.540 | 0.545 | 0.558 | 0.547 | 0.562 |

* p < 0.010, ** p < 0.05, *** p < 0.01. Notes: This table regresses moisture growth and various additional controls (listed in the leftmost column) on annualized rural population growth. Regressions 2–6 employ state fixed effects. Rural population is calculated as total district population minus urban population.

## FIGURE A. IV. Distribution of Annualized City Population Growth



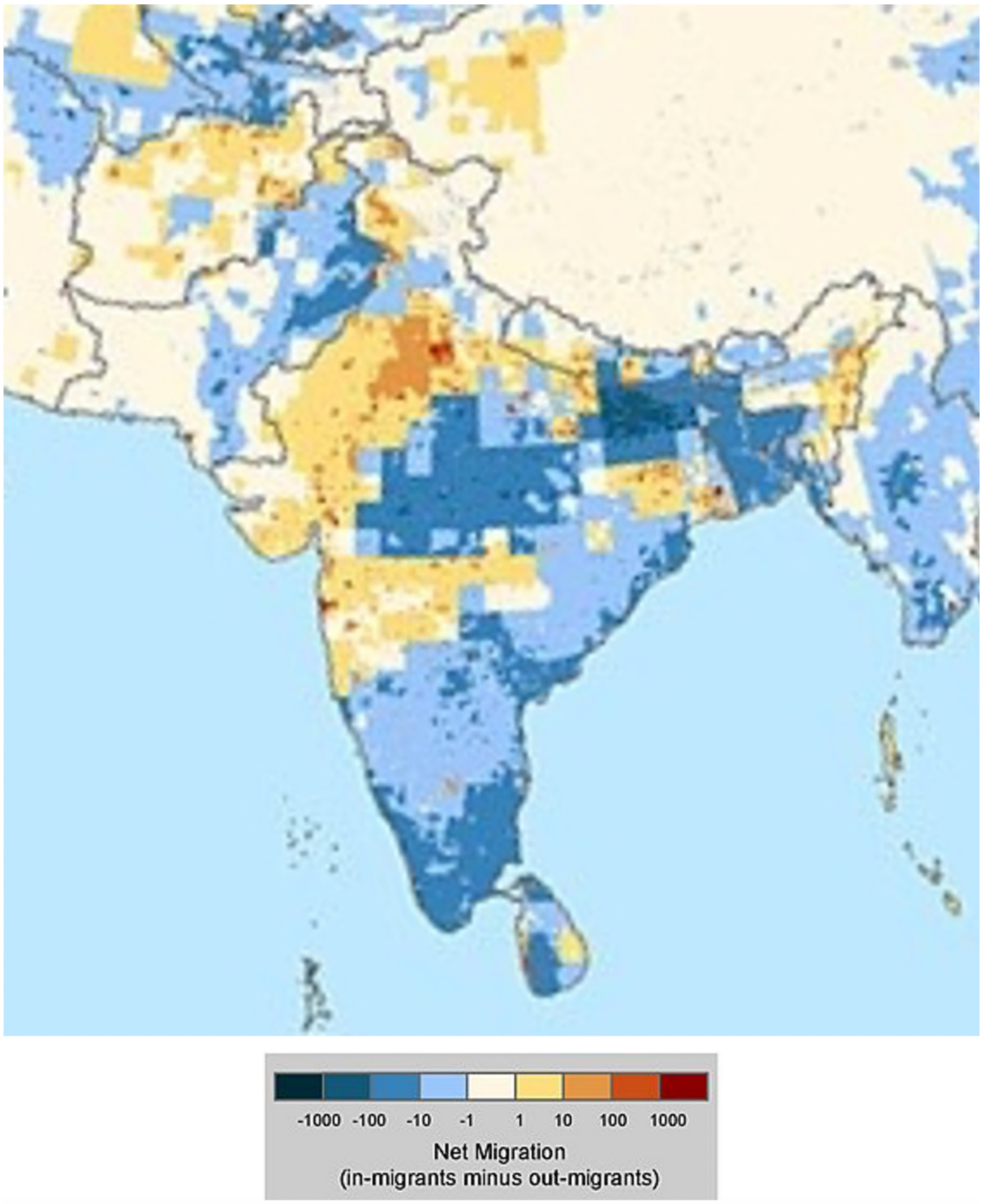

Source: Author's calculations using data from the 2011 Census of India. Graph shows distribution of annualized city population growth. Annualized city growth is winsorized to three standard deviations from the mean.

## TABLE A. VI. Regression Results: Urban Population Growth by Urban Center, Non-winsorized

| Independent Variable | (1) | (2) | (3) | (4) | (5) | (6) |
|---|---|---|---|---|---|---|
| Baseline urban share | -0.0001<br>(0.0007) | -0.0002<br>(0.0007) | -0.0002<br>(0.0007) | 0.0003<br>(0.0008) | 0.0002<br>(.0007) | \0.0003<br>(0.0008) |
| Baseline moisture | 0.002<br>(0.001) | 0.0006<br>(0.002) | 0.0005<br>(0.002) | 0.0004<br>(0.002) | 0.0003<br>(0.002) | 0.00004<br>(0.002) |
| Coastal | -0.0008<br>(0.002) | 0.002<br>(0.002) | 0.003<br>(0.002) | 0.002<br>(0.002) | 0.002<br>(0.002) | 0.002<br>(0.002) |
| Annualized moisture growth | 0.097<br>(0.101) | 0.400***<br>(0.142) | 0.398***<br>(0.143) | 0.396***<br>(0.145) | 0.354***<br>(0.143) | 0.349**<br>(0.146) |
| Log(Baseline industry emissions) | - | - | -0.0007<br>(0.0006) | -0.001**<br>(0.0005) | - | -0.001**<br>(0.0005) |
| Annualized industry emissions growth | - | - | - | 0.059**<br>(0.024) | - | 0.060**<br>(0.025) |
| Baseline precipitation | - | - | - | - | -7.23e-06<br>(0.00001) | -3.08e-06<br>(0.00001) |
| Annualized precipitation growth | - | - | - | - | 0.031<br>(0.032) | 0.027<br>(0.032) |
| Baseline air temperature | - | - | - | - | 0.002**<br>(0.0008) | 0.002**<br>(0.0008) |
| Annualized air temperature growth | - | - | - | - | 0.081<br>(0.052) | 0.092*<br>(0.053) |
| State fixed effects | NO | YES | YES | YES | YES | YES |
| Constant | 0.021***<br>(0.007) | 0.021***<br>(0.008) | 0.010<br>(0.025) | 0.002<br>(0.013) | 0.020*<br>(0.008) | -0.003<br>(0.14) |
| Adjusted R-Squared | 0.0037 | 0.086 | 0.087 | 0.093 | 0.088 | 0.095 |

* p < 0.010, ** p < 0.05, *** p < 0.01. Notes: This table regresses moisture growth and various additional controls (listed in the leftmost column) on annualized city population growth. Regressions 2–6 employ state fixed effects. All regressions cluster standard errors at the district level.

**FIGURE A. V. Internal Migration Flows in India**




Source: NASA Socioeconomic Data and Applications Center (de Sherbinin et al. 2015). This map shows net migration flows throughout India from 1990–2000. Areas that have experienced an inflow of migrants have, by and large, also experienced moisture growth from 1971–2011.

# ENDNOTES

1 Cities also have an important role to play in climate change mitigation efforts; however, the focus of this section is climate adaptation, so discussion of mitigation efforts is left to other studies.

2 There is an important distinction to be made between urbanization and urban growth. As Tacoli et al. (2015) explain, urbanization is defined as “the proportion of the total national population living in areas classed as urban.” This is also called the “national urban population share.” Urban growth, on the other hand, refers to “the absolute number of people living in areas classed as urban.” These transitions are driven by different processes, so it is important to investigate them both separately and together.

3 Construction and justification for the use of climatic moisture is provided in later sections.

4 India’s governing apparatus is divided into 28 states and 8 territories. According to the 2011 census, states were further partitioned into 640 districts; this number has increased to 741 as of 2020. As outlined in the “Methods” section, this paper employs the district names and boundaries from the 2011 census to allow for panel comparison.

5 The data identification and analysis methods follow closely in the precedent set by Hendersen, Storeygard, and Deichmann (2017).

6 Cities originally classified in the 1971 census are henceforth referred to as “established cities.” In subsequent Indian censuses, new towns were identified and classed as urban areas; these emergent “census towns” are, on average, much smaller than established cities. The reclassification of new towns is captured in the urban share and total urban population statistics.

7 Willmott and Feddema’s construction yields a clearly bounded measure, as opposed to Thornthwaite’s unbounded measure, thus allowing for clearer and more consistent interpretation.

8 See Shuttleworth and Wallace (1985) for a full description of the methods used to calculate potential evapotranspiration (PET). This method is considered to be stronger than others because it combines separate estimates for soil evapotranspiration and canopy transpiration. Stannard (1993) and Abeysiriwardana, Muttil, and Rathnayake (2022) also provide straightforward explanations of the methods to calculate PET, along with a comparison between the Shuttleworth-Wallace method, Penman-Monteith method (a simpler, more commonly used calculation) and other accepted PET-calculation methods.

9 Willmott and Feddema’s index is recentered around 1 to allow for calculation of the annualized growth rate.

10 Willmott and Feddema estimate moisture at spatial resolution of 0.5x0.5 degrees. A full overview of the methods used to calculate gridded data on moisture, temperature, and precipitation can be found in Willmott and Matsuura (1999).

11 The 2011 Census of India is the most recent census. Due to the Covid-19 pandemic, the 2021 Census of India has been continually postponed.

12 In order, the population thresholds for Class I–VI cities are as follows: 100,000 and above; 50,000–99,999; 20,000–49,999; 10,000–19,999; 5,000–9,999; and less than 5,000.

13 Non-short cycle emissions data includes “all fossil CO2 sources, such as fossil fuel combustion, non-metallic mineral processes, metal (ferrous and non-ferrous) production processes, urea production, agricultural liming, and solvents use” (Crippa et al. 2021a). EDGAR primarily uses data from the International Energy Agency World Energy Balances.

14 “Reclassification” refers to “the shift of a settlement from one category (rural) to another (urban) when its boundaries expand, it is annexed to an adjacent settlement, or it passes specific criteria such as a population density threshold” (Menashe-Oren and Bocquier 2021).

15 “Census towns” refers to areas that are classified as urban for the purposes of the census based on the following criteria: “population exceeds 5,000; at least 75% of main male working population is employed outside the agricultural sector; minimum population density of 400 persons per km2” (Mitra and Tripathi 2021).

# BIBLIOGRAPHY

Abeysiriwardana, Himasha Dilshani, Nitin Muttil, and Upaka Rathnayake. 2022. "A Comparative Study of Potential Evapotranspiration Estimation by Three Methods with FAO Penman–Monteith Method Across Sri Lanka." *Hydrology* 9, no. 11 (November): 206. https://doi.org/10.3390/hydrology9110206.

Abiy, Anteneh Z. et al. 2019. "Drought and Climate Teleconnection and Drought Monitoring." In Assefa M. Melesse, Wossenu Abtew, and Gabriel Senay (eds.). *Extreme Hydrology and Climate Variability: Monitoring, Modelling, Adaptation and Mitigation*. Cambridge, MA: Elsevier, 2019.

Adger, W. Neil, et al. 2020. "Urbanization, Migration, and Adaptation to Climate Change." *One Earth* 3, no. 4 (October): 396–399. https://doi.org/10.1016/j.oneear.2020.09.016.

Alstone, Peter, Dimitry Gershenson, and Daniel M. Kammen. 2015. "Decentralized Energy Systems for Clean Electricity Access." *Nature Climate Change* 5, no. 4 (April): 305–314. https://doi.org/10.1038/nclimate2512.

Asher, Sam et al. 2022. "The Long-Run Development Impacts of Agricultural Productivity Gains: Evidence from Irrigation Canals in India." Structural Transformation and Economic Growth, Working Paper 004. https://steg.cepr.org/publications/long-run-development-impacts-agricultural-productivity-gains-evidence-irrigation.

Barrett, Christopher B., Ariel Ortiz-Bobea, and Trinh Pham. 2021. "Structural Transformation, Agriculture, Climate and the Environment." The SC Johnson College of Business Applied Economics and Policy, Working Paper Series No. AEP WP 2021-02 (January). Available at SSRN: http://dx.doi.org/10.2139/ssrn.3933252.

Barrios, Salvador, Luisito Bertinelli, and Eric Strobl. 2006. "Climatic Change and Rural–Urban Migration: The Case of Sub-Saharan Africa." *Journal of Urban Economics* 60, no. 3 (November): 357–371. https://dx.doi.org/10.1016/j.jue.2006.04.005.

Blakeslee, David, Ram Fishman, and Veena Srinivasan. 2020. "Way Down in the Hole: Adaptation to Long-Term Water Loss in Rural India." *American Economic Review* 110, no. 1 (January): 200–224. https://www.aeaweb.org/articles?id=10.1257/aer.20180976.

Bohra-Mishra, Pratikshya, Michael Oppenheimer, and Solomon M. Hsiang. 2014. "Nonlinear Permanent Migration Response to Climatic Variations but Minimal Response to Disasters." *Proceedings of the National Academy of Sciences of the United States of America (PNAS)* 111, no. 27 (July): 9780–9785. https://www.jstor.org/stable/23802664.

Buis, Alan. 2022. "Steamy Relationships: How Atmospheric Water Vapor Amplifies Earth's Greenhouse Effect." National Aeronautic and Space Administration, Global Climate Change: Vital Signs of the Planet. February 8. https://climate.nasa.gov/ask-nasa-climate/3143/steamy-relationships-how-atmospheric-water-vapor-amplifies-earths-greenhouse-effect.

Bustos, Paula, Bruno Caprettini, and Jacopo Ponticelli. 2016. "Agricultural Productivity and Structural Transformation: Evidence from Brazil." *American Economic Review* 106, no. 6 (June): 1320–1365. https://www.jstor.org/stable/43861124.

Bustos, Paula, Gabriel Garber, and Jacopo Ponticelli. 2019. "Capital Accumulation and Structural Transformation." Global Poverty Research Lab, Working Paper No. 17-107 (November). Available at SSRN: http://dx.doi.org/10.2139/ssrn.3126453.

Census of India. 2022. "Decadal variation in population 1901 - 2011." Office of the Registrar, General & Census Commissioner, India. Updated June 1. https://censusindia.gov.in/nada/index.php/catalog/43333.

———. [n.d.]. "Towns and urban agglomerations classified by population size class in 2011 with variation between 1901 and 2011 - Class I, II, III, IV, V, & VI." Office of the Registrar, General & Census Commissioner, India. Available to download at: https://censusindia.gov.in/nada/index.php/catalog/?page=1&sk=Towns%20and%20urban%20agglomerations%20classified%20by%20population%20size%20class%20in%202011&sort_by=popularity&sort_order=desc&ps=15.

Chattopadhyay, N. and M. Hulme. 1997. "Evaporation and Potential Evapotranspiration in India Under Conditions of Recent and Future Climate Change." *Agricultural and Forest Meteorology* 87, no. 1 (November): 55–73. https://doi.org/10.1016/S0168-1923(97)00006-3.

Christiaensen, Luc, Joachim De Weerdt, and Yasuyuki Todo. 2013. "Urbanization and Poverty Reduction: The Role of Rural Diversification and Secondary Towns." *Agricultural Economics* 44, no. 4–5 (July–September): 435–447. https://doi.org/10.1111/agec.12028.

Crippa, Monica et al. 2019. *Fossil CO2 and GHG Emissions of All World Countries – 2019 Report*. Luxembourg: Publications Office of the European Union. https://doi.org/10.2760/687800.

———. 2021a. "EDGAR v6.0 Greenhouse Gas Emissions." Dataset. European Commission, Joint Research Centre. http://data.europa.eu/89h/97a67d67-c62e-4826-b873-9d972c4f670b.

———. 2021b. *Fossil CO2 and GHG Emissions of All World Countries – 2021 Report*. Luxembourg: Publications Office of the European Union. https://op.europa.eu/en/publication-detail/-/publication/45c88a84-2d65-11ec-bd8e-01aa75ed71a1.

Datta, Pritha, Bhagirath Behera, and Dil Bahadur Rahut. 2022. "Climate Change and Indian Agriculture: A Systematic Review of Farmers' Perception, Adaptation, and Transformation." *Environmental Challenges* 8 (August): 100543. https://doi.org/10.1016/j.envc.2022.100543.

Dell, Melissa, Benjamin F. Jones, and Benjamin A. Olken. 2012. "Temperature Shocks and Economic Growth: Evidence from the Last Half Century." *American Economic Journal: Macroeconomics* 4, no. 3 (July): 66–95. https://www.jstor.org/stable/23269794.

———. 2014. "What Do We Learn from the Weather? The New Climate–Economy Literature." *Journal of Economic Literature* 52, no. 3 (September): 740–798. https://www.jstor.org/stable/24434109.

de Sherbinin, Alex et al. 2015. "Global Estimated Net Migration Grids by Decade: 1970-2000." Dataset. Palisades, NY: NASA Socioeconomic Data and Applications Center (SEDAC). http://dx.doi.org/10.7927/H4319SVC.

Ellis, Peter and Mark Roberts. 2016. *Leveraging Urbanization in South Asia: Managing Spatial Transformation for Prosperity and Livability*. Washington, DC: The World Bank Group. https://openknowledge.worldbank.org/entities/publication/f1ba8d07-e6d1-5b8e-8a16-899838f1c884.

Glaeser, Edward L. 2012. *Triumph of the City: How Our Greatest Invention Makes Us Richer, Smarter, Greener, Healthier and Happier*. New York: Penguin Books.

Gornall, Jemma et al. 2010. "Implications of Climate Change for Agricultural Productivity in the Early Twenty-First Century." *Philosophical Transactions of the Royal Society B: Biological Sciences* 365, no. 1554 (September): 2973–2989. https://royalsocietypublishing.org/doi/10.1098/rstb.2010.0158.

Henderson, J. Vernon, Adam Storeygard, and Uwe Deichmann. 2017. "Has Climate Change Driven Urbanization in Africa?" *Journal of Development Economics* 124 (January): 60–82. https://dx.doi.org/10.1016/j.jdeveco.2016.09.001.

IPCC (Intergovernmental Panel on Climate Change). 2022. *Climate Change 2022: Impacts, Adaptation and Vulnerability*. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig,

S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge, UK: Cambridge University Press. https://report.ipcc.ch/ar6/wg2/IPCC_AR6_WGII_FullReport.pdf.

Liu, Maggie, Yogita Shamdasani, and Vis Taraz. 2020. "Climate Change, Structural Transformation, and Infrastructure: Evidence from India." Unpublished Manuscript. Available at: https://www.dropbox.com/s/8hyyk9x0sg2tfwb/LST_updated.pdf?dl=0.

Jan van Duijne, Robbin and Jan Nijman. 2019. "India's Emergent Urban Formations." *Annals of the American Association of Geographers* 109, no. 6 (November): 1978–1998. https://doi.org/10.1080/24694452.2019.1587285.

Kulkarni, Ashwini et al. 2020. "Precipitation Changes in India." In R. Krishnan et al. (eds.). *Assessment of Climate Change Over the Indian Region.* Singapore: Springer. https://link.springer.com/chapter/10.1007/978-981-15-4327-2_3.

Kumar, Rohitashw and Harender Raj Gautam. 2014. "Climate Change and its Impact on Agricultural Productivity in India." *Journal of Climatology & Weather Forecasting* 2, no. 1 (April): 1000109. https://doi.org/10.4172/2332-2594.1000109.

Menashe-Oren, Ashira and Philippe Bocquier. 2021. "Urbanization Is No Longer Driven by Migration in Low- and Middle-Income Countries (1985–2015)." *Population and Development Review* 47, no. 3 (September): 639–663. https://doi.org/10.1111/padr.12407.

Mitra, Arup and Sabyasachi Tripathi. 2021. "Rural Non-Farm Sector: Revisiting the Census Towns." *Environment and Urbanization ASIA* 12, no. 1 (March): 148–155. https://doi.org/10.1177/0975425321990324.

Neumann, Barbara et al. 2015. "Future Coastal Population Growth and Exposure to Sea-Level Rise and Coastal Flooding – A Global Assessment." PloS ONE 10, no. 3 (March): e0118571. https://doi.org/10.1371/journal.pone.0118571.

Ozturk, Ugur et al. 2022. "How Climate Change and Unplanned Urban Sprawl Bring More Landslides." *Nature* 608, no. 7922 (August 8): 262–265. https://www.nature.com/articles/d41586-022-02141-9.

Peri, Giovanni and Akira Sasahara. 2019. "The Impact of Global Warming on Rural-Urban Migrations: Evidence from Global Big Data." National Bureau of Economic Research, Working Paper 25728 (April). http://www.nber.org/papers/w25728.

Rigaud, Kanta Kumari et al. 2018. *Groundswell: Preparing for Internal Climate Migration.* Washington, DC: The World Bank Group. https://openknowledge.worldbank.org/bitstream/handle/10986/29461/WBG_ClimateChange_Final.pdf.

Shepard, Donald. 1968. "A Two-Dimensional Interpolation Function for Irregularly-Spaced Data." *Proceedings of the 1968 23rd ACM National Conference* (January): 517–523. https://dl.acm.org/doi/10.1145/800186.810616.

Shuttleworth, W. James and J. S. Wallace. 1985. "Evaporation from Sparse Crops – An Energy Combination Theory." *Quarterly Journal of the Royal Meteorological Society* 111, no. 469 (July): 839–855. https://doi.org/10.1002/qj.49711146910.

Small, Christopher, Vivien Gornitz, and Joel E. Cohen. 2000. "Coastal Hazards and the Global Distribution of Human Population." *Environmental Geosciences* 7, no. 1 (March): 3–12. https://doi.org/10.1046/j.1526-0984.2000.71005.x.

Small, Christopher and Robert J. Nicholls. 2003. "A Global Analysis of Human Settlement in Coastal Zones." *Journal of Coastal Research* 19, no. 3 (Summer): 584–599. https://www.jstor.org/stable/4299200.

Stannard, David I. 1993. "Comparison of Penman-Monteith, Shuttleworth-Wallace, and Modified Priestley-Taylor

Evapotranspiration Models for Wildland Vegetation in Semiarid Rangeland." *Water Resources Research* 29, no. 5 (May): 1379–1392. https://doi.org/10.1029/93WR00333.

Tacoli, Cecilia et al. 2015 "Urbanisation, Rural-Urban Migration and Urban Poverty." International Institute for Environment and Development, IIED Working Paper (March). https://www.jstor.org/stable/pdf/resrep01308?acceptTC=true&coverpage=false&addFooter=false

Thornthwaite, C.W. 1948. "An Approach Toward a Rational Classification of Climate." *Geographical Review* 38, no. 1 (January): 55–94. https://doi.org/10.2307/210739.

Tuholske, Cascade et al. 2019. "Variability in Urban Population Distributions Across Africa." *Environmental Research Letters* 14, no. 8 (August): 085009. https://iopscience.iop.org/article/10.1088/1748-9326/ab2432.

———. 2021. "Global Urban Population Exposure to Extreme Heat." *Proceedings of the National Academy of Sciences of the United States of America (PNAS)* 118, no. 41 (October 4): e2024792118. https://doi.org/10.1073/pnas.2024792118.

Willmott, Cort J., Clinton M. Rowe, and William D. Philpot. 1985. "Small-Scale Climate Maps: A Sensitivity Analysis of Some Common Assumptions Associated with Grid-Point Interpolation and Contouring." *The American Cartographer* 12, no. 1 (April): 5–16. https://doi.org/10.1559/152304085783914686.

Willmott, Cort J. and Johannes J. Feddema. 1992. "A More Rational Climatic Moisture Index." *Professional Geographer* 44, no. 1 (February): 84–88. http://climate.geog.udel.edu/~climate/publication_html/Pdf/WF_ProfGeog_92.pdf.

Willmott, Cort J. and Kenji Matsuura. 1999. "Willmott and Feddema's Moisture Index Archive: Gridded Monthly Climatologies." Version 1.01. August 1. http://climate.geog.udel.edu/~climate/html_pages/README.im.html.

———. 2018a. "Terrestrial Air Temperature: 1900 – 2017 Gridded Monthly Time Series." Dataset, Version 5.01. Updated August. http://climate.geog.udel.edu/~climate/html_pages/Global2017/README.GlobalTsT2017.html.

———. 2018b. "Terrestrial Precipitation: 1900 – 2017 Gridded Monthly Time Series." Dataset, Version 5.01. Updated August. http://climate.geog.udel.edu/~climate/html_pages/Global2017/README.GlobalTsP2017.html.

———. 2018c. "Willmott and Feddema's Moisture Index Archive: Monthly Time Series (1900 – 2017)." Dataset, Version 4.01. Updated August. http://climate.geog.udel.edu/~climate/html_pages/Global2017/README.GlobalImTs2017.html.

World Bank. 2021. "Advancing Climate Action through an Urban Lens." World Bank Group, September 8. https://www.worldbank.org/en/topic/urbandevelopment/brief/climate-action-through-an-urban-lens.

UN Habitat (United Nations Human Settlements Programme). [n.d.]. "Climate Change." United Nations. Accessed April 12, 2022. https://unhabitat.org/topic/climate-change.

UNFCC (United Nations Framework Convention on Climate Change). 2017. "Initiatives in the Area of Human Settlements and Adaptation: Summary Report by the Secretariat." Subsidiary Body for Scientific and Technological Advice, Forty-sixth session. April 25. https://unfccc.int/documents/9664.

Zhang, Tianyi et al. 2019. "Irrigation Impacts on Minimum and Maximum Surface Moist Enthalpy in the Central Great Plains of the USA." *Weather and Climate Extremes* 23 (March): 100197. https://doi.org/10.1016/j.wace.2019.100197.

Zimmer, Andrew et al. 2020. "Dynamics of Population Growth in Secondary Cities across Southern Africa." *Landscape Ecology* 35, no. 11 (November): 2501–2516. https://link.springer.com/article/10.1007/s10980-020-01086-6.

**To learn more about the Charter Cities Institute, visit:**
**chartercitiesinstitute.org**

CHARTER CITIES
INSTITUTE

**Follow us on Twitter | Like us on Facebook**