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ORIGINAL PAPER

Global warming and urbanization

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Abstract

Analyzing 118 countries between 1960 and 2016, we find that higher temperatures correlate with higher urbanization rates in the long run, where this relationship is much more pronounced than any short-term linkage. The long-run relationship between global warming and urbanization is also conditional upon country-specific conditions. This long-run association is especially relevant in poorer and more agriculture-dependent countries with an urban bias as well as in initially non-urban countries in hotter climate zones. We also provide suggestive evidence that warming contributes to losses in agricultural productivity and to pro-urban shifts in public goods provision and that the global warming-urbanization nexus is partly mediated through these channels. Consequently, we argue that the estimated long-run relationship between temperature and urbanization partly captures the potential impact of increasing temperatures on urbanization via a rural push (by impairing agriculture) and an urban pull (via an increased demand for public goods primarily supplied in cities).

Keywords Climate change · Global warming · Urbanization · Rural–urban migration · Panel vector error correction models

JEL Classification Q54 · R23

1 Introduction

Among the most important global trends of the twentieth and twenty-first century are the phenomena of urbanization and global warming. Urbanization refers to an increase in a country's urban relative to its rural population (United Nations

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2014; IOM 2015). In 1950, approximately 30% of the world's population lived in urban areas. By the 2010s, this share had increased to over 50%, and approximately 66% of the world's population is projected to live in cities by 2050 (United Nations 2014). Global warming refers to the observed heating of the Earth's land and ocean surfaces since the mid-twentieth century. This process is mainly due to anthropogenic greenhouse gas emissions such as carbon dioxide, methane and nitrous oxide (IPCC 2014). From 1880 to 2012, global temperatures increased by approximately 0.85 °C, on average, when considering the combined land and ocean surfaces (IPCC 2014: 40). What is more, average surface temperatures are estimated to be between 0.4 and 2.6 °C higher in the 2046–2065 period compared to the 1986–2005 period, with further increases being likely for the remainder of the twenty-first century (IPCC 2014: 60).

In this contribution, we examine whether the trends in urbanization and global warming are related. We focus on global warming because persistent increases in temperature are the starting point for a broader range of similarly persistent phenomena associated with global climate change, including, e.g., rising sea levels, shrinking glaciers, the increased prevalence of extreme weather-events (e.g., heat waves, floods) and changing precipitation patterns (IPCC 2014). For our empirical analysis, we use country-level data on temperature for 118 countries between 1960 and 2016 and link this data to national urbanization rates. Consistent with the literature, we argue that these urbanization rates primarily reflect rural–urban migration (e.g., IOM 2015). We show that higher temperatures are related to higher urbanization rates (and thus rural–urban migration) in the long run, where such long-term linkages are much more pronounced than any short-term ones. What is more, we find that the relationship between global warming and urbanization is particularly relevant to countries characterized by relative economic and institutional underdevelopment and strong dependence on agriculture, suggesting that these countries are less adaptive and more vulnerable to global warming. Furthermore, we find that the relationship between global warming and urbanization matters more strongly to initially non-urban countries in hotter climate zones, which points to further heterogeneity in the global warming-urbanization nexus. Finally, we provide suggestive evidence that warming contributes to losses in agricultural productivity and pro-urban shifts in public goods provision and that the global warming-urbanization nexus is partly mediated through these channels. Consequently, relying on a push–pull model of internal migration, we argue that global warming promotes migration both by contributing to poorer rural conditions (e.g., by adversely affecting agricultural production and wages) and an increased relative attractiveness of urban centers (e.g., by increasing demand for public goods primarily provided in cities).

Our analysis is related to earlier empirical efforts that link other indicators of climate variation (e.g., shortages in rainfall, natural disasters) to urbanization and find that such variation tends to promote urbanization, especially in poorer countries (e.g., Barrios et al. 2006; Annez et al. 2010; Gray and Mueller 2012; Mueller et al. 2014; Beine and Parsons 2015; Cattaneo and Peri 2016; Mastrorillo et al. 2016; Maurel and Tuccio 2016; Henderson et al. 2017).[1] We add to these studies in four ways. First, we employ statistical tests and econometric methods to adequately account for various data features such as non-stationarity, cointegration and cross-sectional dependence. Disregarding these features (such as the obvious trending in urbanization and global warming) may have seriously biased previous empirical estimates of the relationship between temperature and urbanization. Second, our study is the first to differentiate between the short-run and long-run linkages between global warming and urbanization. This is advantageous because the short- and long-run consequences of increasing temperatures may differ, e.g., with respect to the nature and size of estimated relationships. We identify these short- and long-run effects using the dynamic fixed-effects estimators in a panel vector error correction framework. Third, within this framework we can identify heterogeneous linkages in the global warming-urbanization nexus that are governed by country-specific mediators. While previous research has already shown that differences in the levels of economic development, the role of the manufacturing sector, dependence on agriculture and agricultural policies may moderate the association between rising temperatures and urbanization (e.g., Cattaneo and Peri 2016; Maurel and Tuccio 2016; Henderson et al 2017; Peri and Sasahara 2019; Chort and de la Rupelle 2022), we extend this analysis by also looking at previously unappreciated mediators such as initial urban bias, i.e., the preferential treatment of urban center with respect to public investment as well as access to markets, institutions and public goods. Fourth, we explore the role of potential transmission channels by means of a suggestive mediation analysis, studying both the influence of potential mediators on the warming-urbanization relationship and the association between temperature and variables that reflect the proximate mechanisms. Here, we can corroborate earlier evidence that rising temperatures undermine agricultural productivity (e.g., Beine and Parson 2015; Cattaneo and Peri 2016; Maurel and Tuccio 2016), but we further consider a hitherto unappreciated transmission variable, showing that temperature increases also correlate with stronger differences in the provision of public goods between urban and rural areas.

The remainder of this paper is organized as follows. In Sect. 2, we discuss in more detail how increasing temperatures may be related to urbanization. In Sects. 3 and 4, we introduce our data and examine it for the presence of cross-sectional dependence, panel unit roots and the existence of a long-run relationship between rising temperatures and urbanization. In Sect. 5, we run a series of panel vector error correction models to estimate the short- and long-run effect of increasing temperatures on urbanization. We also study how the global warming-urbanization nexus is moderated by a variety of country-specific conditions and explore potential mechanisms. Section 6 concludes.

[1] Besides inducing rural–urban migration, climate change and shocks may also be related to a migratory response in the form of rural-rural migration and international migration. For instance, these alternative responses have been studied in Findley (1994), Marchiori and Schumacher (2011), Potts (2012), Beine and Parsons (2015), Cattaneo and Peri (2016), Maurel and Tuccio (2016) and Helbling and Meierrieks (2021). See also Berlemann and Steinhardt (2017) for a review of the literature.

2 Global warming and urbanization

As changes in urbanization rates mostly reflect changes in rural–urban migration (e.g., United Nations 2014; IOM 2015), to understand how increasing temperatures may be related to urbanization, we need to understand how it may be related to rural–urban migration. In the *push–pull framework* developed in Lee's (1966) seminal paper, migration decisions primarily depend on (1) conditions in the migrants' area of origin, (2) conditions associated with the migrants' area of destination, and (3) migration costs.[2] Applying this framework to *rural–urban migration*, it predicts that this kind of migration will occur when (1) conditions in rural areas deteriorate (i.e., the *rural push* increases), (2) conditions in the cities improve (i.e., the *urban pull* increases) and/or when (3) migration costs decrease (Lee 1966). Consistent with the push–pull model of internal migration, we argue that global warming influences the relative attractiveness of rural and urban areas and thus overall patterns of internal migration.

2.1 The global warming-urbanization nexus

There are two transmission channels that are most relevant to explaining the relationship between global warming and urbanization: *agriculture* and the *provision of public goods*.

Agriculture Increasing temperatures are expected to negatively affect agricultural production. For instance, higher temperatures may contribute to water stress, depress plant growth and exacerbate the spread of plant pests and diseases (Hertel and Lobell 2014). Indeed, many empirical studies conclude that rising temperatures reduce agricultural output (for an overview, see Carter et al. 2018).

Wages in the agricultural sector already tend to be low due to the prevalence of rural surplus labor, i.e., underemployment in agriculture that depresses wages. We expect higher temperatures to correlate with reduced agricultural productivity and, consequently, even lower agricultural wages. Indeed, Harris and Todaro (1970) show that lower wages in the agricultural sector will increase the expected wage differential between the rural and urban sector, increasing both the rural push and urban pull. This, in turn, means that the diversified urban economy can directly tap into the reservoir of rural surplus labor by offering higher wages and inducing more migration towards urban areas.

Public goods Increasing temperatures are also expected to increase demand for public goods. For instance, they may create additional demand for *healthcare*, given that higher temperatures are linked to excess morbidity and mortality, e.g., due to heat strokes and other cardiovascular ailments, difficulties during pregnancy, mood disorders and exhaustion and even suicidality as well as the spread of infectious diseases

[2] Alternative economic theories of rural–urban migration are reviewed in, e.g., Bhattacharya (1993) and Etzo (2008).

when increasing temperatures allow insects and rodents that are disease vectors (e.g., mosquitos for malaria) to find new habitats in regions that were previously too cold (e.g., Berry et al. 2010; Deschenes 2014; Wu et al. 2016; Burke et al. 2018; Chen et al. 2020; Meierrieks 2021; Hajdu and Hajdu 2021; for overviews of the nexus between climate change, human health and migration, see, e.g., McMichael et al. 2012; Schwerdtle et al. 2018). Similarly, there may be increased demand for *order and security*, given that global warming may undermine social stability. For instance, there is evidence that higher temperatures may be conducive to aggression and violent crime and facilitate internal armed conflict, e.g., in the form of civil wars, due to economic dissatisfaction and increased resource scarcity (e.g., as arable land disappears) that can plausibly accompany global warming (e.g., Cohn 1990; Anderson et al. 2000; Miguel et al. 2004; Burke et al. 2015a).

Crucially, cities offer better access to public goods (e.g., hospitals, public health services, the police) compared to rural areas (e.g., Galea et al. 2005) due to scale economies, better access to infrastructure and internal and external markets as well as a greater availability of educated specialists. As demand for public goods grows due to increasing temperatures, this may consequently make rural–urban migration more attractive. What is more, global warming may also induce shortages in the provision of public goods, e.g., as increasing temperatures depress economic output (e.g., Burke et al. 2015b) and thus reduce tax income and result in cuts to public spending and investment. Such cuts are more likely to affect rural areas, which may, in turn, further increase the divide in the supply of public goods between rural and urban areas.

In sum, we argue that higher temperatures are simultaneously related to the rural push by adversely influencing the agricultural sector (thus lowering the opportunity costs of staying at home) and to the urban pull by affecting the provision of public goods in favor of the urban centers (thus increasing the benefits of migrating to the cities), leading to the following hypothesis:

H1:Increasing temperatures are related to higher levels of urbanization.

2.2 Counterarguments

Despite the previous arguments as to why global warming might be positively related to rural–urban migration, it is also possible that global warming is negatively related to it. Indeed, some studies find that migration flows may decrease due to climate change especially in low-income countries (e.g., Cattaneo and Peri 2016; Peri and Sasahara 2019).

For one, urban areas may be more vulnerable than rural areas to some aspects of climate change. For instance, by nature of being usually located on the coast or near rivers, cities are also more vulnerable to rising sea levels and increased flooding that may result from global warming (e.g., IPCC 2014: 67). This, in turn, may also result in internal migration to non-urban, less-susceptible areas.

For another, increasing temperatures may be impediments to rural–urban migration. Migration is associated with specific costs (e.g., travelling costs). If rising temperatures adversely affect human health and undermine security, this may consequently increase *migration costs* (e.g., by necessitating additional spending on security), which may disincentivize migration to the cities.

Furthermore, if rising temperatures induce economic downturns (e.g., by depressing agricultural production), this may reduce the resources available to finance rural–urban migration. That is, such downturns worsen *liquidity constraints* of potential internal migrations (e.g., by reducing agricultural income), meaning that potential migrants will have a reduced ability to pay migration costs, again possibly preventing rural–urban migration (e.g., Cattaneo and Peri 2016: 128).

Natural urban population growth tends to be lower than natural rural population growth (e.g., Ledent 1982; Buckley 1998; Garenne and Joseph 2002). Thus, if global warming indeed poses a sufficiently strong barrier to internal migration, we could also find support for the following hypothesis:

H2: Increasing temperatures are related to lower levels of urbanization.

2.3 Short-run and long-run linkages

Since global warming is an incremental process, we also differentiate between its short- and long-run relationship with urbanization. Here, we expect increasing temperatures to have more prominent association with warming in the long than short run. For instance, temperature increases from one year to the next will be hardly noticeable for a (potential) internal migrant. Consequently, such incremental changes in temperature are not expected to make it more likely that migrants reach their stress-threshold (Wolpert 1966) that makes them leave their home areas, in contrast to other push factors such as war and famines. What is more, (potential) migrants usually tend to prefer staying over migrating given the costs and uncertainty associated with migration (Lee 1966).

In the long run, however, we expect the incremental changes in temperature to have cumulative and disruptive socio-economic effects. These effects function as important pull and push factors in the context of global warming, leading to widening differences between origin (rural) and destination (urban) regions, especially in the long run. As already theorized by Lee (1966: 53–54), it is this long-run and growing differential that leads to an increase in migration flows over time:

H3: Increasing temperatures are related to urbanization more strongly in the long than in the short run.

2.4 Conditional linkages

Finally, it is plausible that the relationship between temperature and rural–urban migration is conditional upon country-specific politico-economic and demographic conditions. In detail, we discuss—and empirically examine—below whether this relationship is moderated by initial climate conditions and urbanization levels as well as country-specific differences in economic development, agriculture and rural–urban inequalities.

Initial temperature It seems plausible that the relationship between global warming and urbanization is more pronounced in countries located in hotter parts of the world. For instance, agricultural productivity may only decline at elevated temperatures due to increased water and heat stress, while being barely affected at lower temperatures (e.g., Burke et al. 2015b). Thus, the effect of increasing temperatures on the rural push (by lowering agricultural productivity, wages and unemployment) may be more strongly felt in countries with higher initial temperatures compared to countries located in comparatively colder climates.

H4: The relationship between increasing temperatures and urbanization is particularly strong in relatively hot countries.

Initial urbanization Like initial climate conditions, different initial levels of urbanization may also affect the global warming-urbanization nexus. Here, we expect a stronger association in less urbanized countries. For instance, higher initial levels of urbanization are associated with a number of specific urban problems such as congestion, social alienation and slumification (e.g., Jedwab et al. 2017). These problems, in turn, are expected to make rural–urban migration less attractive. Ceteris paribus, increasing temperatures therefore ought to be less influential in already more urban countries.

H5: The relationship between increasing temperatures and urbanization is particularly strong in countries with a relatively low level of initial urbanization.

Economic development Rural–urban migration might also be smaller in richer countries that have the financial and technological capacity to effectively adapt to global warming (e.g., Fankhauser and McDermott 2014). For instance, these countries are expected to exhibit the technology (e.g., the wide-spread availability of air conditioning) and public health infrastructure to combat adverse effects of rising temperatures on human health also in rural areas, thereby decreasing the incentives to move from the countryside to the cities.

H6: The relationship between increasing temperatures and urbanization is particularly strong in relatively poor countries.

Agriculture Our discussion above highlights the potentially key role of agriculture as a transmission channel from increasing temperature to changing urbanization patterns. For example, increasing temperatures may hurt agricultural production and wages, creating a rural push, especially when cities offer alternative means of employment, e.g., in the tradable manufacturing sector (e.g., Henderson et al. 2017). Thus, we also expect a stronger relationship between temperature changes and urbanization in countries that are more dependent on agriculture as a source of national income.

H7: The relationship between increasing temperatures and urbanization is particularly strong in countries with a relatively large agricultural sector.

Urban bias Finally, the relationship between global warming and urbanization may be conditional upon the rural areas' vulnerability and adaptive capacity to rising temperatures. For instance, adequate provision of public health and security in rural areas—the demand for which is expected to grow in response to increasing temperatures—may decrease the urban pull due to global warming. Yet, vulnerability and adaptive capability are, in turn, determined by the access of the countryside to public goods, institutions and resources in comparison to the urban centers. In many countries, a so-called *urban bias* prevails (e.g., Lipton 1977), where urban areas are prioritized over the hinterland, e.g., in terms of public investment as well as access to markets, institutions and public goods. When such urban bias exists, it ought to produce greater incentives for rural–urban migration compared to countries with (relative) equality between urban and rural areas, given that the rural push and urban pull due to increasing temperatures is less likely to be accommodated (via public investment, increased public goods provision etc.).

H8: The relationship between increasing temperatures and urbanization is particularly strong in countries with a more pronounced urban bias.

3 Data

To test our hypotheses regarding the global warming-urbanization nexus, we use data on climate and urbanization for a sample of 118 countries for the 1960–2016 period. A country list is provided in the appendix. The summary statistics are reported in Table 1.

Our country coverage is dictated by the fact that our dataset needs to be fully balanced for the panel methods we employ below. Therefore, we cannot consider countries for which data is not available for the whole observation period; for instance, this concerns some very small island countries as well as countries that only gained independence in the 1980s and 1990s.[3] The observation period is likewise chosen to allow for the use of panel methods that necessitate a fully balanced panel. For

[3] Furthermore, we do not consider city-states (e.g., Singapore) for which urbanization rates do not vary over time.

Table 1 Summary statistics

Variable	N*T	Mean	Std. dev	Min	Max
Urbanization	6726	47.48	24.07	2.08	97.92
Temperature (in °C)	6726	19.35	7.58	−7.3	29.6
Population Size (in 1,000,000)	6726	38.73	132.06	0.06	1,378.67
GDP p.c. (in 1000 US$)	6726	10.63	12.45	0.16	84.54
Democracy	6726	0.28	0.22	0.01	0.83
Youth dependency ratio	6726	65.08	24.26	18.45	112.37
Access to education	6726	0.17	1.47	−3.10	3.47
Share of young males	6726	45.66	7.95	23.05	61.44
Precipitation (in 1000 mm)	6726	1.11	0.73	0.02	3.68
Ground frost frequency	6726	0.270	4.17	0	20.72
Cloud cover	6726	55.20	14.71	13.77	96.21
Potential evapotranspiration	6726	3.41	0.99	1.15	6.57
Value added in agriculture	5634	18.34	15.12	0.37	89.41
Urban–rural access to public goods	6373	0.15	1.32	−2.71	2.96

instance, data on many control variables we use in our subsequent analyses is not available for earlier time periods.

Our sample covers approximately 90% of the world population over a period of time that saw both rapid urban growth and substantial increases in temperature (e.g., IPCC 2014; United Nations 2014), allowing for a comprehensive study of the global warming-urbanization nexus between 1960 and 2016. That said, our analysis is not suited to make statements about the relationship between temperature and urbanization before 1960 and especially not before the industrial era when urbanization was far less wide-spread and global warming non-existent.[4] For analyses of the pre-industrial history of urbanization and the potential role of climatic factors in pre-industrial urban growth, we thus refer to, e.g., De Vries (1984) and Bairoch (1988).

3.1 Urbanization

To test our hypotheses, we would, ideally, want to relate annual sub-national variation in temperature to annual sub-national (internal) migration flows (e.g., from rural to urban areas within a specific country). Unfortunately, a comprehensive dataset on annual internal migration does not exist (e.g., United Nations 2013). While census data will allow for cautious statements about internal migration in specific

[4] The relationship between temperature and urbanization in pre-industrial times (i.e., before 1800) could be studied by using palaeoclimatological and other historical data. Such datasets are, of course, affected by considerable uncertainty, e.g., given that climate data are reconstructed and urbanization data relies on incomplete historical sources. Nevertheless, while it is well beyond the scope of our study, a historical analysis of the temperature-urbanization relationship may be a fruitful endeavor for future research to arrive at a more complete picture of the climate-urbanization relationship.

countries, differences in data collection, accuracy, definitions, time horizons, etc. between national censuses do not allow for cross-country comparisons (United Nations 2013). In particular, a lack of data on rural–urban migration for most developing countries will not allow us to systematically differentiate between the impact of increasing temperatures in developed and developing economies.[5]

We therefore follow Beine and Parsons (2015), Cattaneo and Peri (2016), and Maurel and Tuccio (2016) and argue that the urbanization rate approximates rural–urban migration. The urbanization rate is the number of a country's inhabitants living in urban areas (as defined by the respective national statistical offices) as a share of a country's total population. The data are drawn from the *World Development Indicators*, *WDI* (World Bank 2017).

There is indeed a consensus that urbanization is primarily the result of migration, so that changes in urbanization rates reflect rural–urban migration balances (e.g., IOM 2015). Besides rural–urban migration, there are three factors that may also explain changes in the urbanization rate over time. First, urbanization rates may increase over time when urban population growth is higher than rural population growth. In most parts of the world, however, urban population growth tends to be lower than rural population growth (e.g., Ledent 1982; Buckley 1998; Garenne and Joseph 2002); consequently, we would expect urbanization rates to actually decrease if natural differences in population growth between rural and urban areas would be influential. Second, it is possible that urbanization rates change when rural regions are reclassified into urban centers by national statistical offices (Jedwab et al. 2017). As noted by the International Organization for Migration (IOM 2015), however, this "official statistics effect" will usually also be due to rural–urban migration rather than due to natural population growth (e.g., IOM 2015). Third, urbanization rates may be affected by international migration to urban centers. However, we expect the impact of international migration to be rather low, given that internal migration is much more common than international migration due to, e.g., the lower costs of internal compared to international migration (e.g., UNDP 2009; United Nations 2013; IOM 2015). What is more, international migration is expected to be a significant driver of urbanization primarily in the developed economies of the Global North (e.g., IOM 2015); by contrast, our analysis—especially by allowing for heterogeneous effects—more strongly focuses on the role of global warming in the more vulnerable countries and communities of the Global South. In sum, we therefore anticipate the influence of alternative determinants of the urbanization rate to be benign compared to the influence of internal migration, so that we are confident that changes in the urbanization rate indeed approximate rural–urban migration.

Figure 1 illustrates the development of the urbanization rate between 1960 and 2016 as an in-sample average for the countries in our sample. We detect a clear

[5] In a recent paper, Peri and Sasahara (2019) try to overcome this lack of data at the sub-national level by relating imputed migration data to climate data at the grid-cell-level (where each cell has a $0.5° \times 0.5°$ resolution) for 10-year intervals between 1970 and 2000. Our study complements Peri and Sasahara (2019), e.g., in that we use annual data at the country-level, especially allowing us to also differentiate between the short- and long-run effects of increasing temperatures on urbanization at a different level of aggregation.

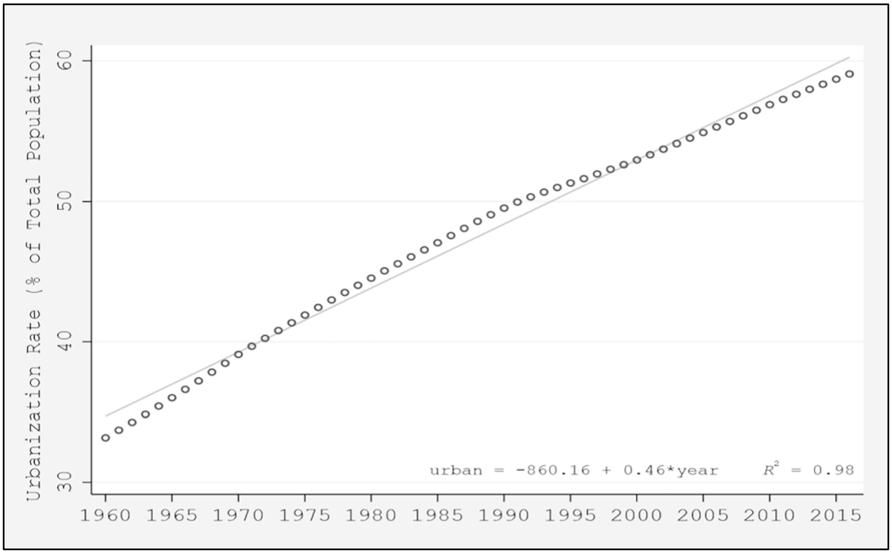

Fig. 1 In-sample mean urbanization rate, 1960–2016

positive trend in the urbanization rate. In fact, this trend is almost perfectly linear, with the urbanization rate being estimated to grow by 0.46 percentage points per year, increasing from 33.17 in 1960 to 59.07 in 2016 for the countries in our sample. Figure 1 is therefore consistent with the notion of a rapid urbanization since the 1950s (e.g., United Nations 2014; IOM 2015).

3.2 Temperature data

Our primary climate indicator is *temperature* (in °C) per country-year observation. That is, we average all weather data on temperature for a specific country and year of interest, correcting for differences in grid sizes and elevation between weather stations within the same grid. Weather data are from the *Climate Research Unit of the University of East Anglia*.[6] This research unit provides climate data collected from various weather stations at a 0.5°×0.5° grid resolution. As the urbanization data is only available at the country-level, we also spatially aggregate the climate data to the country-level.

Figure 2 visualizes the global trend in temperature for the countries in our sample between 1960 and 2016. As with the urbanization rate, we find evidence of a clear positive trend in temperatures, estimating that the mean temperature (for the countries in our sample) increased by 0.021 °C per year, resulting in a rise from 19.16 °C in 1960 to 20.19 °C in 2016. This increase in temperatures by approximately 1 °C illustrated in Fig. 2 is consistent with the notion of global warming discussed in, e.g., IPCC (2014).

[6] See http://www.cru.uea.ac.uk/data.

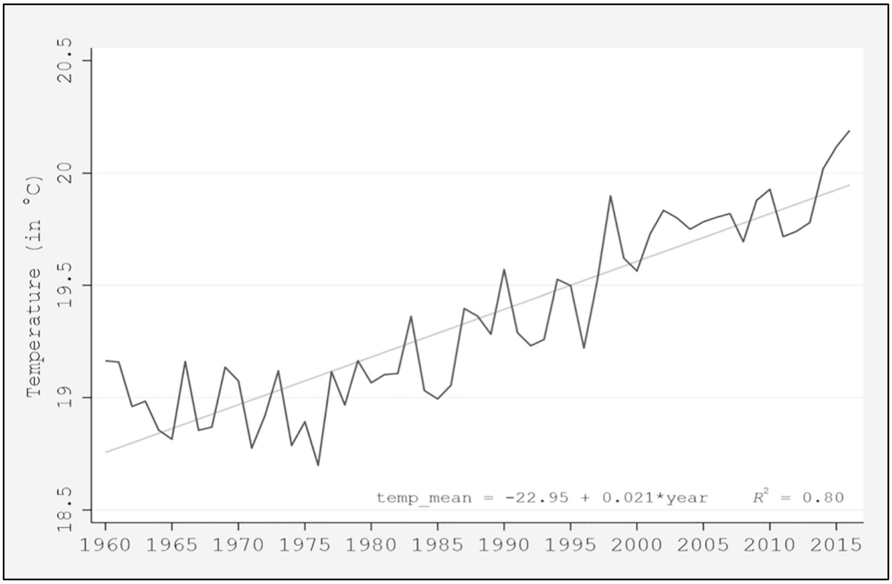

Fig. 2 In-sample mean temperature, 1960–2016

3.3 Cross-sectional dependence

Before we begin our empirical analysis of the nexus between global warming and urbanization, it is necessary to examine our data for the presence of *cross-sectional dependence*. Cross-sectional dependence refers to the interdependency of variables of interest between cross-sections (in our case, countries), where this interdependency may be due to, e.g., common shocks or spillover effects (Sarafidis and Wansbeek 2012).

For both variables of interest, cross-sectional dependence is likely. First, urbanization rates may be correlated across countries, e.g., due to the influence of international trade and cross-border effects from armed conflict. Second, temperatures across countries are also likely to be correlated (Auffhammer et al. 2013). For instance, common exposure to inter-country climate fluctuations (e.g., the El Niño–Southern oscillation) may lead to similar effects on temperatures in proximate countries.

We assess the presence of cross-sectional dependence using the bias-adjusted LM test of Pesaran et al. (2008) and the test for weak cross-sectional dependence of Pesaran (2015). Our test results are reported in Table 2. They strongly indicate that the urbanization and the temperature data are affected by cross-sectional dependence. Given that common exposure to shocks (e.g., from regional climate phenomena) or spillover effects (e.g., from regional economic or political crises) is likely relevant to the patterns of temperature and urbanization, the findings reported in Table 2 are highly intuitive. Important for our subsequent empirical analysis, the findings call for the use of econometric methods that are robust to the presence of cross-sectional dependence. For

Table 2 Test for panel cross-sectional dependence

Variable	LM test statistic (*p* value)	Weak CD test statistic (*p* value)	Mean absolute correlation
Urbanization	352.70 (0.00)***	542.17 (0.00)***	0.89
Temperature	352.70 (0.00)***	362.47 (0.00)***	0.58

H_0 for LM test = no correlation among cross-sectional units. H_0 for weak CD test = weak cross-sectional dependence (i.e., correlation between cross sections converges to zero as the number of cross sections goes to infinity; under strong dependence (H_a), the correlation would converge to a constant)

$^{***}p < 0.01$ (rejection of H_0)

instance, disregarding cross-sectional dependence may otherwise potentially invalidate inference from statistical tests (Sarafidis and Wansbeek 2012).

4 Panel unit root and cointegration tests

4.1 Panel unit root tests

Figures 1 and 2 indicate that both urbanization rates and temperature exhibit long-run positive trends. Data series that trend over time are often found to be non-stationary (i.e., to contain a unit root). As shown in the pioneering study by Granger and Newbold (1974), disregarding non-stationarity may give rise to the so-called spurious regression problem. That is, a regression model including two non-stationary variables may prove problematic because significance tests on the regression coefficients from such spurious regressions are invalid (Granger and Newbold 1974; Kao 1999). For instance, it is possible that significance tests indicate a "significant" relationship between variables when in fact none exists (Granger and Newbold 1974; Kao 1999).

We test for the presence of unit roots in the urbanization and temperature data using the panel unit root tests developed by Pesaran (2007), Herwartz and Siedenburg (2008), and Demetrescu and Hanck (2012). Importantly, all tests are robust to cross-sectional dependence (conforming to our tests for cross-sectional dependence reported in Table 2) and serial correlation. Finally, the latter two tests are also robust to heteroskedasticity, which is also highly likely to plague macro-panels like the one we consider in this paper.

The test results reported in Table 3 strongly suggest that all data series are non-stationary in levels but become stationary after the first-difference is taken. Thus, all data series show evidence of I(1) behavior.

4.2 Tests for panel cointegration

When two variables are non-stationary and integrated of the same order, they may be cointegrated (Engle and Granger 1987). Cointegration refers to the existence of a stationary linear combination of two non-stationary variables. Accounting for

Table 3 Panel unit root test results

Variable	CADF test statistic (*p* value)	HS test statistic (*p* value)	DH test statistic (*p* value)
Level data			
Urbanization	– 1.85 (0.22)	– 0.27 (0.39)	1.71 (0.96)
Temperature	– 3.59 (0.00)***	– 0.22 (0.41)	– 0.09 (0.46)
First-differenced data			
Δ Urbanization	– 2.02 (0.00)***	– 2.15 (0.02)**	– 1.52 (0.06)*
Δ Temperature	– 5.73 (0.00)***	– 5.08 (0.00)***	– 5.59 (0.00)***

Δ = First-difference operator. CADF test = test by Pesaran (2007). For this test, the standard augmented Dickey-Fuller regressions are augmented with cross-sectional averages of lagged levels and first-differences of the individual series. Also, extreme *t*-values are truncated to avoid size distortions due to serial correlation. HS test = Test by Herwartz and Siedenburg (2008). DH test = test by Demetrescu and Hanck (2012). Both tests are robust to heteroskedasticity and cross-sectional dependence. Serial correlation accounted for by pre-whitening (lag length selection via Akaike information criterion). For all considered tests, country-specific constants are included as deterministic components

*$p < 0.1$; **$p < 0.05$; ***$p < 0.01$ (rejection of H_0 of nonstationarity)

cointegration therefore allows us to adequately model the long-run (cointegrating) relationship between two non-stationary variables (Engle and Granger 1987). Disregarding cointegration, by contrast, would result in model misspecification and incorrect inferences because the equilibrium relationship between two variables is not accounted for (e.g., Engle and Yoo 1987; MacDonald and Kearney 1987; Kao 1999).

Indeed, following our theoretical considerations outlined above, it is highly plausible that urbanization and global warming are cointegrated, sharing a long-run equilibrium relationship. For example, global warming is expected to result in persistent reductions in agricultural activity (e.g., Carter et al. 2018), which, in turn, may create a persistent rural push, incentivizing persistent rural–urban migration.

To examine whether the data series are cointegrated, we use the panel cointegration tests of Kao (1999), Pedroni (1999) and Westerlund (2007). The former two tests always examine the null hypothesis of no panel cointegration against the alternative hypothesis that the panel is cointegrated as a whole (Kao 1999; Pedroni 1999). The test by Westerlund (2007) also includes test variants where we consider the null hypothesis of no panel cointegration against the alternative hypothesis that at least one cross section is cointegrated. Importantly, all tests take into account cross-sectional dependence: the Kao (1999) and Pedroni (1999) do so by subtracting the cross-sectional means, while Westerlund (2007) employs a bootstrapping approach.

In addition to investigating bivariate cointegration between urbanization and temperature, for all cointegration tests we also run multivariate specifications that include several controls that may also be cointegrated with urbanization; this ought to mitigate concerns about the omission of relevant variables and spurious cointegration test results. When choosing these controls, we follow the literature on the determinants of urbanization (e.g., Ades and Glaeser 1995; Barrios et al. 2006; Fox 2012). In detail, we control for (1) *population size*, with the data coming from the WDI; (2) *per capita income*, using data from the *Maddison Project* (Bolt et al.

2018); (3) *democracy*, employing a participatory democracy index from the *V-DEM Dataset* (Coppedge et al. 2019); (4) the *youth dependency ratio*, defined as the population ages 0–15 divided by the population ages 16–64 (WDI data); and (5) *education*, proxied by an index of education equality that measures access to basic education (V-DEM data).

The panel cointegration tests are reported in Table 4. They provide strong evidence that urbanization and temperature are cointegrated. Similarly, there is compelling evidence in favor of cointegrating relationships between urbanization, temperature and the additional control variables. As noted above, evidence in favor of panel cointegration implies that a long-run (stable) equilibrium relationship between urbanization and global warming exists which needs to be modelled accordingly.

5 Empirical analysis

5.1 Traditional fixed-effects approach

We begin our empirical analysis by considering various fixed-effects approaches to estimate the relationship between temperature increases and urbanization; this approach is in the fashion of, e.g., Cattaneo and Peri (2016) and Maurel and Tuccio (2016). We do so for two reasons. First, we want to assess how our fixed-effects estimates compare to earlier findings, given that our dataset is larger especially with respect to the time dimension. Second, we want to examine whether a traditional fixed-effects approach is affected by misspecification issues concerning cross-sectional dependence, non-stationarity and panel cointegration.

For a traditional fixed-effects approach, our estimation equation has the following form for country i and year t:

$$\text{urban}_{it} = \alpha_i + \beta temp_{i,t} + \gamma \text{X}'_{i,t} + \tau_t + \epsilon_{it} \quad (1)$$

Here, *urban* and *temp* refer to the urbanization rate and temperature. The vector X contains the control variables we introduced above (population size, per capita income, democracy, youth dependency ratio and education equality). Equation (1) also considers a set of country- and year-fixed effects (α and τ) and the error term (ε).

We report our fixed-effects estimates in Table 5. We find that higher temperatures are usually associated with lower urbanization levels. This is in line with earlier results reported in, e.g., Cattaneo and Peri (2016) and Peri and Sasahara (2019). What is more, we show that this finding is driven by low-income countries, which is consistent with *H2*. For instance, this may be due to liquidity constraints, where warming sufficiently reduces (agricultural) income to trap the population in rural areas especially in poorer countries.

There are, however, three concerns about the estimates reported in Table 5. First, the regression residuals are usually contaminated by cross-sectional dependence, as indicated by the results of the test for weak cross-sectional dependence of Pesaran (2015). We can accommodate this issue by employing Driscoll-Kraay standard

Table 4 Panel cointegration test results

Test	Associated test statistics of test variant (p value)			
Kao (1999)	Unadjusted Dicker-Fuller t-statistic	Augmented Dicker-Fuller t-statistic	Dicker-Fuller t-statistic	Modified Dicker-Fuller t-statistic
Bivariate	5.30 (0.00)***	−2.54 (0.00)***	−1.61 (0.05)**	−1.32 (0.09)*
Multivariate	−3.44 (0.00)***	−3.17 (0.00)***	−2.62 (0.00)***	−2.07 (0.02)**
Pedroni (1999)	Augmented Dicker-Fuller t-statistic (panel-specific AR parameter)	Phillip-Perron t-statistic (panel-specific AR parameter)	Augmented Dicker-Fuller t-statistic (same AR parameter)	Phillip-Perron t-statistic (same AR parameter)
Bivariate	6.87 (0.00)***	7.54 (0.00)***	−0.70 (0.24)	2.26 (0.01)**
Multivariate	15.77 (0.00)***	10.78 (0.00)***	13.10 (0.00)***	9.01 (0.00)***
Westerlund (2007)	G_t	G_a	P_t	P_a
Bivariate	−1.55 (0.05)**	−8.11 (0.00)***	−18.89 (0.02)**	−6.99 (0.01)**
Multivariate	1.023 (0.37)	−1.29 (0.00)***	−9.42 (0.01)**	−1.04 (0.05)**

In all cases, the dependent variable is the urbanization rate, while the independent variable is temperature. In the multivariate case, the following independent variables are also included: population size; GDP p.c.; democracy; youth dependency ratio; education equality. All test variants include panel means as deterministic components and include lags (as well as leads in case of the Westerlund test) to account for serial correlation. H_0 for the Kao and Pedroni tests = no cointegration for all cross-sectional units. H_0 for G_t and G_a = no cointegration for at least one cross-sectional unit. H_0 for P_t and P_a = no cointegration for the panel as a whole. Kao and Pedroni test subtract cross-sectional means to account for cross-sectional dependence. p values for Westerlund test robust to cross-sectional dependence as they are obtained from bootstrapping with 100 replications

$^{*}p<0.1$; $^{**}p<0.05$; $^{***}p<0.01$ (rejection of respective H_0)

Table 5 Fixed-effects estimates

Specification	(1) Fixed effects	(2) Add controls	(3) Add trends	(4) Driscoll-Kraay SE	(5) Drop HI countries	(6) (5) and Heterogeneity	(7) Add trends to (6)
Temperature	−1.246	−1.101	−0.999	−0.999	−1.068		
	(0.347)***	(0.339)***	(0.447)**	(0.452)**	(0.493)**		
Temperature [MI countries]						−0.414	−0.790
						(0.570)	(0.648)
Temperature [LI countries]						−2.689	−1.345
						(1.083)**	(0.795)*
Country-fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year-fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year-fixed effects × regional dummies	No	No	Yes	Yes	No	No	Yes
Year-fixed effects × LI dummy	No	No	No	No	No	No	Yes
Further controls	No	Yes	Yes	Yes	Yes	Yes	Yes
Within-R^2	0.69	0.71	0.75	0.75	0.78	0.78	0.82
Number of observations	6608	6608	6608	6608	4760	4760	4760
CD test (p value)	(0.00)***	(0.00)***	(0.00)***	(0.00)***	(0.78)	(0.27)	(0.04)**
CADF test (p value)	(1.00)	(1.00)	(1.00)	(1.00)	(1.00)	(1.00)	(1.00)

Further controls = population size; GDP p.c.; democracy; youth dependency ratio; education equality. MI/LI = middle-income and low-income countries according to World Bank Classification. Cluster-robust standard errors in parentheses. Driscoll-Kraay standard errors in specification (4)

* $p < 0.1$; ** $p < 0.5$; *** $p < 0.01$

errors (Driscoll and Kraay 1998). These standard errors are robust to general forms of cross-sectional dependence. Reassuringly, using these standard errors (model (4), Table 5) yields similar standard error estimates. Second, and more importantly, the regression residuals are also always contaminated by non-stationarity, as indicated by the corresponding results of Pesaran's (2007) panel unit root test. This clearly hints at a spurious regression issue, given that the "noise" (residual) also provides—in violation of the regression model assumptions—a signal (e.g., Kao 1999: 5). As shown in Table 5, year-fixed effects, various trends and the inclusion of additional controls cannot accommodate for this issue. Third, our fixed-effects estimates also do not adequately account for (panel) cointegration between temperature and urbanization, which is expected to aggravate misspecification concerns and produce incorrect inferences (e.g., Engle and Yoo 1987; MacDonald and Kearney 1987; Kao 1999).

In sum, the results of Table 5 show that previous approaches to the global warming-urbanization nexus that rely on fixed-effects models produce results that are likely spurious. In contrast, below we employ an empirical approach that accommodates cross-sectional dependence, non-stationarity and panel cointegration. In this manner, we clearly set ourselves apart from previous empirical analyses of the global warming-urbanization nexus (e.g., Barrios et al. 2006; Annez et al. 2010; Cattaneo and Peri 2016; Maurel and Tuccio 2016; Peri and Sasahara 2019).

5.2 Panel vector error correction model

To accommodate cross-sectional dependence, non-stationarity and panel cointegration when studying the relationship between temperature and urbanization, we estimate a *panel vector error correction model* of the following form:

$$\begin{aligned}\Delta \text{urban}_{it} = \rho^i\left[\text{urban}_{i,t-1} - \theta_i temp_{i,t} - \vartheta X'_{i,t}\right] + \sum_{l=1}^{p-1} \gamma_l^i \Delta urban_{i,t-l} \\ + \sum_{l=1}^{p-1} \delta_l^i \Delta temp_{i,t-l-1} + \sum_{l=1}^{p-1} \tau_l^i \Delta \text{X}'_{i,t-l-1} + \alpha_i + \epsilon_{it}\end{aligned} \tag{2}$$

As above, *urban* and *temp* refer to the urbanization rate and temperature, respectively, while X refers to the usual controls (population size, per capita income, democracy, youth dependency ratio and education equality). Besides these variables, the model also includes country-fixed effects (α) that account for time-invariant factors. For instance, the inclusion of these fixed effects is important due to the role of geographical features (e.g., access to the sea and rivers) in shaping urbanization (Fox 2012). Fixed effects also allow us to account for different initial levels of urbanization and climate conditions. To make valid statistical inference in the presence of cross-sectional dependence, we always employ Driscoll-Kraay standard errors (Driscoll and Kraay 1998). These standard errors are robust to general forms of cross-sectional dependence; furthermore, they are robust to heteroskedasticity and autocorrelation.

Urbanization and temperature as well as the controls are first-differenced (indicated by the first-difference operator Δ) to achieve stationarity; they can enter the model with a lag up to order l.[7] The sum of the coefficients associated with these first differences ($\sum_{l=1}^{p-1} \gamma_l^i$ and $\sum_{l=1}^{p-1} \delta_l^i$, respectively) give us the *short-run relationship* between lagged changes in urbanization and temperature on present changes in urbanization.

To study the *long-run relationship*, the model includes the error-correction term $\rho^i\left[\text{urban}_{i,t-1} - \theta_i temp_{i,t} - \vartheta X'_{i,t}\right]$. This term refers to the stationary linear combination of non-stationary variables and is included to account for panel cointegration, in line with the panel cointegration test result. ρ^i refers to the regression coefficient associated with the effect of the urbanization rate on its first-difference (the so-called speed of adjustment). If this regression coefficient is statistically significant and lies between $[0; -1]$ (implying dynamic stability), a long-run equilibrium relationship between urbanization and temperature exists. In this case, the long-run association between temperature and urbanization is calculated from $[-\theta_i'/\rho^i]$.

In sum, our empirical model allows us to examine—while accounting for cross-sectional dependence, non-stationarity and cointegration—whether higher temperatures correlate with more (*H1*) or less (*H2*) urbanization. It also allows us to contrast the long-term and the short-term relationship between temperature and urbanization, so that we can fully assess—as warranted by in *H3*—the potentially rich dynamics between these variables in both the short and long run.

5.3 Main results

Our panel vector error correction estimates are reported in Table 6. As an important preamble, the reported regression diagnostics now indicate that the respective regression residuals are no longer (in comparison to the fixed-effects approach reported in Table 5) contaminated by non-stationarity, suggesting that our panel vector error correction approach has successfully accommodated the issue of non-stationarity emerging from the time-series dimension of our panel data.

As shown in Table 6, we find that higher temperatures are associated with less urbanization in the short run. These findings are in line with *H2*. For instance, climate shocks may momentarily disincentivize urbanization by inducing adverse economic shocks (e.g., related to agricultural production) that may make it prohibitively costly for some individuals to migrate to the urban centers, in line with arguments by, e.g., Cattaneo and Peri (2016) and Peri and Sasahara (2019). However, in terms of size these negative short-run associations appear to be benign. For instance, referring to model (3) in Table 6, our estimates suggest that a 1 °C increase in temperature is linked to a reduction of the urbanization rate by less than 0.03 percentage points.

[7] While our fixed-effects model includes a lag (or multiple lags) of the dependent variable as predictors, our time dimension is sufficiently large so that the dynamic panel bias is negligible (Judson and Owen 1999).

Table 6 Main results

	(1)	(2)	(3)
Short-run estimates			
$\sum \Delta$ Urbanization coefficients	0.905	0.902	0.903
	(0.025)***	(0.025)***	(0.025)***
$\sum \Delta$ Temperature coefficients	−0.033	−0.029	−0.027
	(0.007)***	(0.007)***	(0.006)***
[95% confidence interval]	[−0.048; −0.019]	[−0.043; −0.016]	[−0.039; −0.014]
Long-run estimates			
Error correction	−0.004	−0.004	−0.004
	(0.001)***	(0.001)***	(0.001)***
Temperature	8.930	6.832	5.187
	(1.306)***	(1.434)***	(0.988)***
[95% confidence interval]	[6.369; 11.490]	[4.021; 9.642]	[3.251; 7.123]
Further Controls	None	Population, GDP p.c., democracy	All
Within-R^2	0.85	0.85	0.85
Number of observations	6490	6490	6490
CD test (p value)	(0.00)***	(0.00)***	(0.00)***
CADF test (p value)	(0.00)***	(0.00)***	(0.00)***
Oster's δ associated with long-run temperature coefficient	2.23	1.85	1.62

Dynamic fixed-effects estimates reported. Dependent variable = Δ urbanization. Error correction = $urbanization_{t-1}$ (level-data). Dynamic short-run specification is always l = 1. Further controls = population size; GDP p.c.; democracy; youth dependency ratio; education equality. All controls enter all specifications in first-differences and levels in short- and long-run part of model, respectively. Driscoll-Kraay standard errors in parentheses

*$p < 0.1$; **$p < 0.5$; ***$p < 0.01$

By contrast, we find that increases in temperature are linked to *more* urbanization in the long run, in line with *H1*. This result is always dynamically stable with respect to the cointegration relationship. For example, this long-run correlation is consistent with the argument that temperatures persistently hurt the agricultural sector (depressing rural wages and employment), while at the same time increasing the urban pull, e.g., as urban centers offer easier access to public goods that become more valuable as temperatures increase. Indeed, the long-run association between increasing temperatures on urbanization is much more pronounced than the short-run one, thus supporting *H3* in that increasing temperatures primarily correlate with urbanization in the long run. For example, using the long-run estimates associated with model (3) in Table 6, a 1 °C increase in temperature is associated with a long-run increase of urbanization by approximately 5.19 percentage points. For example, between 1960 and 2016, temperatures in Ecuador (from 21.7 to 22.7 °C) and Nigeria (from 26.8 to 27.8 °C) increased by 1 °C; at the same time, their urbanization rates grew from 33.9 to 63.6 (Ecuador) and 15.4 to 48.7 (Nigeria). According to our estimates, a noticeable share of this increase in urbanization can be linked to the long-run positive relationship between increasing temperatures and urbanization.

In Table 6, we also assess how our estimates change when we introduce additional controls to our model. Indeed, both the short- and long-run association between temperature and urbanization becomes less pronounced—while remaining statistically significant – when further controls are added. This may suggest that omitted variables partially account for this association.[8] Alternatively, one may consider some of the covariates (e.g., population size) to be variables that mediate rather than confound the association between temperature and urbanization. For instance, temperature may affect human fertility (e.g., Lam and Miron 1996; Barreca et al. 2018); fertility, in turn, may drive urbanization due to population growth effects, explaining—in parts—how temperature and urbanization may be linked.[9]

To further study the threat of omitted variable bias with respect to our estimates, we also examine the prevalence of selection bias as a sub-form of the omitted variable bias. For instance, certain unobservable factors may correlate with selection into global warming and subsequent urbanization. To investigate the issue of selection, we calculate the degree of selection on unobservables relative to observables that would be necessary to eliminate the result of a positive long-run association between temperature and urbanization (Oster 2019). As shown in Table 6, the degree of selection (δ) is always larger than unity. Following Oster (2019), values of $\delta > 1$ imply that selection on unobservables must be significantly stronger than selection

[8] At the same time, however, the confidence intervals associated with the short- and long-run associations between temperature and urbanization tend to overlap between specifications rather strongly, suggesting that the influence of omitted variables does not appear to be overwhelming.

[9] For instance, Berlemann and Steinhardt (2017: 366) refer to this issue as the "bad controls" or "overcontrolling" problem. They (2017: 366) argue that in order to estimate the "total effect of climatic variation on migration, empirical models need to exclude potential outcomes of climate change." According to this argument, the results reported in model (1) of Table 6 then give us the total correlation between temperature and urbanization, while the inclusion of potential outcomes of global warming (models (2) and (3) of Table 6) is expected to reduce this total correlation.

on observables to explain away our result, making it unlikely that our results are fully driven by unobservables.

Finally, to further assess the influence of omitted variables on our estimates, we also examine how the inclusion of additional controls and the replacement of existing controls with alternative variables affects our estimates. In detail, we (1) consider the inclusion of additional controls for trade openness (WDI data) as well as economic inequality and a rule of law index (both V-DEM data), (2) run a specification where per capita income enters in squared form to allow for a non-linear relationship between income and internal migration (e.g., such a hump-shape migration pattern may be due to the fact that low levels of income mean that individuals cannot afford migration, while high levels of income reduce incentives to migrate), (3) replace all control variables with alternative measures to assess whether the measurement of the various controls affects our estimates (more information on the measurement of these alternative covariates is provided in Supplementary Table 1). As reported in Supplementary Table 1, neither the inclusion of additional controls nor the replacement of existing controls with alternative indicators matters to our main finding: in line with *H2*, higher temperatures are associated with less urbanization in the short run. Consistent with *H1* and *H3*, however, the long-term effect of temperature on urbanization is much more pronounced, where higher temperatures are associated with higher levels of urbanization in the long run. These robustness checks ought to further ameliorate omitted variable concerns.

5.4 Robustness checks

5.4.1 Variants of baseline model

In this sub-section, we consider various empirical modifications to investigate the robustness our main results. We begin by considering some variants of our baseline model. The results are reported in Table 7.

First, we allow all (first-differenced) variables to enter the model with two or three lags. We find that our main results concerning a negative short-run and positive long-run association between temperature and urbanization is robust to these more complex short-run dynamics.[10] Second, we consider two alternative ways to operationalize the temperature variable, either weighting temperature by population size (so that more extreme climate conditions in parts of certain countries that are barely inhabited are less influential) or by agricultural land (so that climate conditions are less influential when they are of little use for agricultural production). Reassuringly, we find that alternative operationalizations of temperature do not affect our main results. Third, we consider alternative measurements of urbanization, either using the logged urbanization rate (to accommodate concerns about non-linear effects) and (logged) total urban population (to account for concerns about censoring related to the urbanization rate). We find that there is evidence of a benign negative short-run association between temperature and urbanization that is accompanied by a large

[10] The inclusion of lags beyond the ones reported in Table 7 also does not affect our main findings.

Table 7 Further estimates of relationship between temperature and urbanization

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Climate data	Mean	Mean	Pop	Agri	Mean	Mean	Mean	Mean	Mean
Measurement urbanization	Urban	Urban	Urban	Urban	(ln) Urban	Total (ln) Urban Pop	Urban	Urban	Urban
Sample	Full	Full	Full	Full	Full	Full	Urban < 67%	Temp < 25.2 °C	No OECD
Short-run estimates									
Short-run dynamics	l = 2	l = 3	l = 1	l = 1	l = 1	l = 1	l = 1	l = 1	l = 1
∑ Δ Urbanization coefficients	0.888	0.885	0.904	0.913	0.881	0.894	0.899	0.920	0.901
	(0.026)***	(0.028)***	(0.025)***	(0.018)***	(0.017)***	(0.012)***	(0.029)***	(0.017)***	(0.027)***
∑ Δ Temperature coefficients	−0.054	−0.061	−0.028	−0.023	−0.001	−0.001	−0.024	−0.027	−0.025
	(0.012)***	(0.017)***	(0.006)***	(0.008)***	(0.000)***	(0.000)***	(0.010)**	(0.006)***	(0.008)***
Long-run estimates									
Error correction	−0.004	−0.004	−0.005	−0.004	−0.006	−0.003	−0.005	−0.005	−0.005
	(0.001)***	(0.001)***	(0.001)***	(0.001)***	(0.001)***	(0.001)***	(0.001)***	(0.001)***	(0.001)***
Temperature	6.133	6.486	5.209	5.892	0.117	0.343	5.576	4.104	4.981
	(1.078)***	(1.220)***	(1.001)***	(1.133)***	(0.019)***	(0.063)***	(1.381)***	(0.874)***	(1.095)***
Further controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Within-R^2	0.86	0.86	0.85	0.86	0.88	0.89	0.84	0.89	0.85
Number of observations	6372	6254	6490	6490	6490	6490	4950	4785	5280

Dynamic fixed-effects estimates reported. Dependent variable = Δ urbanization. Error correction = $\text{urbanization}_{t\text{-}1}$ (level-data). Further controls = population size; GDP p.c.; democracy; youth dependency ratio; education equality. All controls enter all specifications in first-differences and levels in short- and long-run part of model, respectively. Pop = temperature data weighted by population size. Agri = temperature data weighted by agricultural land. Driscoll-Kraay standard errors in parentheses

$^{*}p < 0.1$; $^{**}p < 0.5$; $^{***}p < 0.01$

and positive long-run association between both variables. Finally, we consider three sub-samples. There may be concerns that our results are driven by highly urbanized countries; we thus drop from our sample all countries with an average urbanization rate larger than 67% (which corresponds to the 75th percentile of the urbanization variable). The results may also be driven by very hot countries; we therefore also consider a sample where countries with an average temperature above 25.2 °C (75th percentile of the temperature variable) are dropped. Furthermore, Cattaneo and Peri (2016: 131) argue that a focus of on middle- and low-income countries may be especially revelatory about the global warming-urbanization nexus, given that these countries are particularly prone to productivity losses in agriculture due to temperature increases; we thus drop all countries that were OECD members before 1990 from the sample. However, regardless of which sub-sample we consider, we always find our main results supported by the data, suggesting that outliers do not drive our results.

5.4.2 Additional agro-climatic controls

Potentially, temperature correlates with other climatic variables that also share an important relationship with urbanization. For instance, Auffhammer et al. (2013) argue that temperature and precipitation tend to be strongly correlated; indeed, for our sample this correlation is $r=0.31$ ($p<0.01$). Precipitation, in turn, is expected to also affect agricultural production and thus incentives for migration to urban centers. More generally, this discussion implies that we could overestimate the effect of temperature on urbanization when there are other climatic variables that have an independent association with urbanization and correlate with temperature.

We account for this possibility by running additional models where we control for temperature and several agro-climatic variables, namely (1) precipitation (in average 1,000 mm per month), (2) cloud cover (in percent), (3) ground frost frequency (in number of days with ground frost) and (4) potential evapotranspiration (defined as the amount of evaporation that would occur if a sufficient water source were available in mm per day). The data on these climate variables comes from the *Climate Research Unit of the University of East Anglia*.

As shown in Table 8, controlling for these additional agro-climatic variables does not change the main conclusion of our paper. There is also no evidence that these agro-climatic variables themselves are linked to urbanization in the short or long run.[11] These results suggest that the effect of climate change on urbanization primarily emerges via increasing temperatures, as also found by Cattaneo and Peri (2016).

5.4.3 Alternative estimators

Next, we employ two alternative estimation methods to estimate the panel vector error correction models. First, we use the pooled mean-group estimator proposed by Pesaran et al. (1997); this estimator allows for short-run heterogeneity

[11] We also run an additional model where all agro-climatic variables enter model at the same time. Here, we again find that no agro-climatic variable sways urbanization, while temperature continues to correlate with urbanization in the short and long run.

Table 8 Role of other agro-climatic variables

Agro-climatic variable	(1) Precipitation	(2) Cloud cover	(3) Ground frost	(4) Potential evapotranspiration
Short-run estimates				
∑ Δ Urbanization coefficients	0.904	0.904	0.904	0.904
	(0.025)***	(0.025)***	(0.025)***	(0.025)***
∑ Δ Temperature coefficients	−0.027	−0.025	−0.031	−0.028
	(0.006)***	(0.006)***	(0.008)***	(0.008)***
∑ Δ Agro-climate variable coefficients	0.006	0.001	−0.007	0.004
	(0.026)	(0.001)	(0.010)	(0.041)
Long-run estimates				
Error correction	−0.005	−0.005	−0.005	−0.005
	(0.001)***	(0.001)***	(0.001)***	(0.001)***
Temperature	5.131	5.197	6.016	5.409
	(0.904)***	(0.987)***	(0.949)***	(1.078)***
Agro-climate variable	−3.226	0.116	1.600	−1.853
	(5.616)	(0.193)	(1.352)	(4.914)
Further controls	Yes	Yes	Yes	Yes
Within-R^2	0.85	0.85	0.85	0.85
Number of observations	6490	6490	6490	6490

Dynamic fixed-effects estimates reported. Dependent variable = Δ urbanization. Error correction = $\text{urbanization}_{t-1}$ (level-data). Dynamic short-run specification is always l = 1. Further controls = population size; GDP p.c.; democracy; youth dependency ratio; education equality. All controls enter all specifications in first-differences and levels in short- and long-run part of model, respectively. Driscoll-Kraay standard errors in parentheses

$^{*}p<0.1$; $^{**}p<0.5$; $^{***}p<0.01$

(so that the short-run coefficients can vary between countries), while restricting long-run coefficients to be equal across countries. Second, we employ the mean-group estimator of Pesaran and Smith (1995), which allows both the short- and long-run coefficients to vary by country. The use of these methods may be advantageous if we suspect substantial heterogeneity in the data. In this case, pooling the time-series data for all countries and allowing only the intercepts to differ (as in the dynamic fixed-effects approach we otherwise use in this paper) may produce possibly misleading results.

We report our estimation results using the alternative estimators in Supplementary Table 2. Reassuringly, we arrive at empirical results concerning both the short- and long-run relationship between temperature and urbanization that are very similar to those reported for the baseline dynamic fixed-effects panel vector error correction models. What is more, goodness-of-fit measures (adjusted R^2 and root mean square error) suggest that there are only very marginal advantages to using the much more computationally expensive pooled mean-group and mean-group estimators over the dynamic fixed-effects estimator.

5.4.4 Endogeneity concerns

The estimates concerning the relationship between temperature and urbanization can be interpreted in a Granger-causal way. That is, information on past temperature can be used to predict present-day urbanization (e.g., Engle and Granger 1987). To make more stringent causal claims, however, the related estimates ought to not be affected by endogeneity. Here, endogeneity may have three main causes. First, there may be measurement error in temperature. We think that this source of endogeneity is unlikely, given that temperature is measured in a precise and mechanical way. Also, above we have shown (Table 7) that alternative operationalizations of temperature yield comparable results. Second, endogeneity may be due to omitted variable bias. While we cannot fully rule out the role of unobservable latent factors as joint determinants of temperature and urbanization, above (Table 6, Table 7, and Supplementary Table 1) we have shown that our findings survive the inclusion of our variety of potentially relevant controls, while also ameliorating concerns about selection by means of Oster's (2019) approach. Third, endogeneity may be due to reverse causation. Indeed, it is possible that higher levels of urbanization affect temperature, especially in the long run. For instance, this effect may emerge due to deforestation, changes in albedo and increased air pollution due to industrial development and traffic that accompany urbanization.

To address this latter concern, we run a series of two-stage least squares instrumental variable (*IV*) models, where we instrument local temperature by mean-temperature in proximate countries.[12] The idea is that mean-temperature correlates with local temperature, e.g., because both are affected by similar climate forcing events (e.g., volcanic eruptions, changes in the El Niño–Southern Oscillation or changes in aerosol concentration). Thus, our instrument ought to be sufficiently relevant. As shown in Supplementary Table 3, this is indeed the case. At the same time, we show in Supplementary Table 3 that in the IV-setting temperature continues to exert a positive long-run effect on urbanization that is similar in size to our main estimates of Table 6.

A major threat to our IV-strategy is the influence of shocks in proximate countries that correlate with our instrument but also affect local urbanization; for instance, economic growth in proximate countries is expected to correlate with mean-temperature in proximate countries (e.g., Burke et al. 2015b), while also creating economic spillover effects that may affect local urbanization. To address this concern, in Supplementary Table 3 we also present estimates where we explicitly control for a variety of economic, political and demographic shocks in proximate countries. Our main IV-finding of a positive long-run effect of temperature on urbanization survives this robustness check. Still, our instrument does not necessarily satisfy the exclusion restrictions. The results in the appendix are therefore only suggestive of a causal effect of temperature on urbanization.

[12] Proximate countries are located in the same world region as the country of interest. We consider the following 17 regions (WDI data): the Caribbean, Eastern Africa, Eastern Asia, Eastern Europe, Middle Africa, North America, Northern Africa, Northern Europe, Oceania, South America, South-Eastern Asia, Southern Africa, Southern Asia, Southern Europe, Western Africa, Western Asia and Western Europe.

We also assess the other potential direction of causation from urbanization to temperature. In Supplementary Table 4, we report the association between both variables when temperature is the dependent variable. Here, we find that higher levels of urbanization are associated with higher temperatures, especially in the long run. The effect is relatively benign with respect to size: a one-unit increase in urbanization (i.e., a 1 percentage point increase in the urbanization rate) will increase temperatures by 0.014 °C. Furthermore, this estimate is rather sensitive to the inclusion of additional controls, while Oster's δ suggests that little selection is necessary to overturn the positive long-run link between urbanization and temperature. In sum, it is likely that the findings of Supplementary Table 4 are due to omitted variables.

To further study this assumption, we also run a series of IV-models, where urbanization is instrumented by the *share of young males* (ages 15–29) in relation to all working-age males (ages 15–64) (WDI data) The idea is that a large share of young males ought to increase it, given that migration tends to be undertaking of the young and male especially in developing countries. As shown in Supplementary Table 5, this instrument is indeed sufficiently strong. At the same time, the IV-results do not suggest that urbanization causes higher temperatures in the long run once urbanization is instrumented by the share of young males. This finding is in line with our suspicion that endogeneity may drive the results of Supplementary Table 4. As above, however, our instrument may not satisfy the exclusion restriction. For instance, temperature correlates with human fertility (e.g., Lam and Miron 1996; Barreca et al. 2018). Past temperature shocks may have consequently affected the present-day share of young males; at the same time, past temperature shocks may of course correlate with present-day urbanization and temperature through several pathways. As shown in Supplementary Table 5, controlling for fertility and past temperature does not affect the strength of our instrument; we also find that controlling for these variables does not overturn our result of that there is no statistically significant long-run effect of urbanization on temperature. Again, however, the results in the appendix should be cautiously interpreted as being only suggestive of non-causality from urbanization to temperature.

5.5 Conditional effects

So far, we have established that increases in temperature are related to higher levels of urbanization, especially in the long run. However, this relationship may be different depending on country-specific conditions. For one, the effect of increasing temperatures on urbanization may be stronger in initially hot and non-urban countries (*H4* and *H5*, respectively). For another, the effect of increasing temperatures on urbanization may be more pronounced in poor (*H6*) and agriculture-dependent countries (*H7*) exhibiting an urban bias (*H8*).

To test these propositions, we divide up our sample in six different ways. First, data on initial temperatures is employed to classify countries below the 1960 median of mean-temperature (22.0 °C) as *non-hot* and those above the same median as *hot*. Second, we use data on initial urbanization and categorize the countries in our sample that lie below the median 1960 urbanization rate (31.2%) as *non-urban* and those above the median as *urban*. Third, data on GDP p.c. in 1960 drawn from the Maddison Project Database is used to classify countries below the 1960 GDP p.c. median (ca. $3,000) as *poor* and those above as *rich*. Fourth, countries are classified as *agrarian* when the median employment in the agricultural sector in 1960 is above 29.4%; otherwise, they are classified as *non-agrarian*.[13] Fifth, we use the *rural exclusion index* reported in the V-DEM Dataset to classify the countries in our sample as having an *urban bias* when their initial rural exclusion score is above the median (0.64); countries below the median are classified as having *no urban bias*.[14]

Finally, we acknowledge that the various country-specific mediators are rather strongly correlated; bivariate correlations are reported in Supplementary Table 6. For instance, it is well known that less-developed economies are more likely to be in hotter parts of the world and more dependent on agriculture. To account for this fact, we run a (k-means) cluster analysis, creating two country clusters, where countries within the same cluster are similar with respect to their initial levels of urbanization, temperature, economic development and structure as well as urban bias but sufficiently dissimilar to the other cluster. As shown in Supplementary Table 7, the first cluster includes countries characterized by low initial temperatures, high levels of initial urbanization and economic development as well as low levels of initial agricultural employment and weak urban bias. Typical members of this cluster are industrial countries such as Japan, France and the USA but also some emerging economies such as Chile, Colombia and Tunisia. By contrast, the second cluster consists of countries characterized by relatively high initial temperatures, low levels of initial urbanization and economic development as well as high levels of initial agricultural employment and strong urban bias. Members of this cluster include almost all sub-Saharan African economies in our sample (e.g., Burkina Faso and Nigeria) but also developing countries in Latin America and Asia (e.g., Paraguay and Indonesia).

To test whether the relationship between temperature and urbanization is moderated by the aforementioned variables, we estimate a series of panel vector error correction models of the following form:

$$\begin{aligned}\Delta \text{urban}_{it} = \rho^i\left[\text{urban}_{i,t-1} - \theta_{1,i} temp_{i,t} - \theta_{2,i}(temp_{i,t} * MV_i) - \vartheta X'_{i,t}\right] + \\ \sum_{l=1}^{p-1} \gamma_l^i \Delta urban_{i,t-l} + \sum_{l=1}^{p-1} \delta_{1,l}^i \Delta temp_{i,t-l-1} + \sum_{l=1}^{p-1} \delta_{2,l}^i \\ \left(\Delta temp_{i,t-l-1} * MV_i\right) + \sum_{l=1}^{p-1} \tau_l^i \Delta \text{X}'_{i,t-l-1} + \alpha_i + \epsilon_{it}\end{aligned} \quad (3)$$

Equation (3) is an augmented version of Eq. (2) that also includes an interaction effect of the temperature variable with the respective moderating variable (*MV*) in

[13] Data on employment in the agricultural sector is from the *Food and Agriculture Organization of the United Nations* (http://www.fao.org/faostat/en/). In case employment data is not available in 1960, we instead use earliest available datapoint.

[14] The rural exclusion index is a composite indicator (scaled between 0 and 1) that accounts for difference in access to political power and economic opportunities between urban and rural areas, with higher values of the index pointing to a stronger presence of urban bias, meaning that urban areas enjoy political and economic advantages over their rural counterparts (Coppedge et al. 2019).

both the short and long run, where *MV* can either take on the value of 1 (e.g., when a country is categorized as poor according to the criterion outlined above) or 0 (e.g., when a country is considered to be rich using the same criterion). As before, the short- and long-run correlations between temperature and urbanization in countries for which the moderating variable takes on the value 0 can be calculated by summing up the short-run coefficients ($\sum_{l=1}^{p-1} \gamma_l^i$ and $\sum_{l=1}^{p-1} \delta_{1,l}^i$, respectively). When the moderating variable takes on the value 1, we can calculate the associated short-run effect of temperature on urbanization by summing up $\sum_{l=1}^{p-1} \delta_l^i$ and $\sum_{l=1}^{p-1} \delta_{2,l}^i$. Accordingly, the long-run relationship between temperature and urbanization when the moderating variable takes on the value 0 is equal to $[-\theta_{1,i}/\rho^i]$, while it is equal to $[-(\theta_{1,i} + \theta_{2,i})/\rho^i]$ when the moderating variable takes on the value 1.

We report our panel vector error correction estimates in Table 9. Consistent with our expectations, we find that (1) countries located in comparatively hotter parts of the world see a more pronounced and positive long-run relationship between increasing temperatures and urbanization (consistent with *H4*), (2) countries exhibiting lower initial urbanization rates similarly see a stronger and positive long-run correlation with increasing temperatures (in line with *H5*), while countries are also more likely to exhibit a stronger relationship between rising temperatures and urbanization when (3) they are initially poorer (consistent with *H6*), (4) more dependent on agriculture (in line with *H7*) and (5) exhibit a more pronounced initial urban bias (as predicted by *H8*). Perhaps most interestingly, when we use the two clusters from our cluster analysis, we find that there is only a statistically significant positive long-run relationship between rising temperatures on urbanization in countries characterized by less fortunate starting conditions.

In sum, the findings reported in Table 9 are in line with our earlier results in that higher temperatures tend to be related to lower urbanization (in line with *H2*) in the short run, while they are associated with higher urbanization rates (in line with *H1*) in the long run, where these latter linkages are more pronounced than any short-run ones (confirming *H3*). What is more, we find that rising temperatures correlate with urbanization especially in countries that lack resources to adapt (as indicated by low levels of initial GDP p.c.), distribute these resources inadequately (due to a strong urban bias) and are dependent on agricultural production (which tends to be rather sensitive to rising temperatures). For instance, this speaks to earlier studies that find that urbanization rates in countries characterized by comparatively lower levels of economic development and larger agricultural sectors are more vulnerable to changing climate conditions and the (internal and external) migration it induces (e.g., Barrios et al. 2006; Annez et al. 2010; Beine and Parsons 2015; Cattaneo and Peri 2016; Maurel and Tuccio 2016).

5.6 Mediation analysis and exploration of mechanisms

When developing our hypotheses concerning the global warming-urbanization nexus, we argued that rising temperatures may affect urbanization via two transmission channels: agricultural productivity and the provision of public goods. As a final empirical exercise, we examine whether there is evidence in favor of associated

Table 9 Role of moderating variables

	(1)	(2)	(3)	(4)	(5)	(6)
Moderating variable	Initial temperature (1 = hot)	Initial urbanization (1 = low)	Initial GDP p.c. (1 = poor)	Initial employment agriculture (1 = low)	Initial urban bias (1 = strong)	Cluster analysis (1 = poor starting conditions)
Short-run estimates						
∑ Δ Urbanization coefficients	0.903	0.904	0.902	0.902	0.902	0.900
	(0.025)***	(0.025)***	(0.026)***	(0.026)***	(0.027)***	(0.027)***
∑ Δ Temperature coefficients when moderator is = 0	−0.019	−0.024	−0.023	−0.018	−0.029	−0.019
	(0.009)**	(0.008)***	(0.007)***	(0.009)**	(0.009)***	(0.010)**
∑ Δ Temperature coefficients when moderator is = 1	−0.034	−0.033	−0.028	−0.038	−0.011	−0.028
	(0.014)**	(0.015)**	(0.016)*	(0.015)**	(0.014)	(0.014)*
Long-run estimates						
Error correction	−0.005	−0.005	−0.005	−0.005	−0.005	−0.005
	(0.001)***	(0.001)***	(0.001)***	(0.001)***	(0.001)***	(0.001)***
Long-run temperature effect when moderator is = 0	2.668	3.253	2.959	1.904	3.289	1.824
	(1.345)**	(1.259)**	(1.224)**	(1.151)*	(1.591)**	(1.392)
Long-run temperature effect when moderator is = 1	8.091	9.230	7.732	9.695	7.056	8.033
	(1.239)***	(1.098)***	(1.593)***	(1.237)***	(1.451)***	(1.174)***
[Equality of long-run coefficients χ^2-statistic]	[9.49]	[13.59]	[5.29]	[27.23]	[3.02]	[11.54]
[$p > \chi^2$]	[0.00]***	[0.00]***	[0.02]**	[0.00]***	[0.08]*	[0.00]***
Further controls	Yes	Yes	Yes	Yes	Yes	Yes
Within-R^2	0.85	0.85	0.85	0.85	0.85	0.85
Number of observations	6490	6490	6490	6490	6105	6105

Dynamic fixed-effects estimates reported. Dependent variable = Δ urbanization. Error correction = urbanization$_{t-1}$ (level-data). Dynamic short-run specification is always l = 1. Further controls = population size; GDP p.c.; democracy; youth dependency ratio; education equality. All controls enter all specifications in first-differences and levels in short- and long-run part of model, respectively. Driscoll-Kraay standard errors in parentheses

$^{*}p < 0.1$; $^{**}p < 0.5$; $^{***}p < 0.01$

mediation effects. Our mediation analysis consists of two steps. First, we study the association between temperature and the mediator variables. Second, we assess how the long-run coefficient associated with the correlation between temperature and urbanization changes when related mediation variables are included. Finding that temperature correlates with the mediators and that the long-run coefficient becomes noticeably smaller after this inclusion would provide support for the idea that the relationship between increasing temperatures and urbanization is—at least partly—mediated by agricultural productivity and the provision of public goods.

Concerning the mediator variables, agricultural productivity is indicated by the *value added in agriculture as a share of GDP* (WDI data). We measure the provision of public goods using an index of *access to public services distributed by urban–rural location* (V-DEM data). This variable indicates to what extent access to basic public services (security, healthcare, clean water, etc.) is equally distributed between urban and rural areas. We expect rising temperatures to increase demand for these services, while at the same time facilitating their concentration in urban centers.

We report our empirical results in Table 10. Concerning the correlation between temperature and the mediator variables, we find that increases in temperature are linked to lower agricultural productivity and public goods provision in countries with unfavorable starting conditions (as identified by our cluster analysis above) especially in the long run. This is in line with the idea that the association between temperature and urbanization could be mediated by losses in agricultural productivity and pro-urban shifts in public goods provision.[15] Concerning the association between temperature and urbanization, we furthermore show that the long-run coefficient associated with temperature indeed becomes smaller once we control for the two potential mediator variables. This reduction in size is also statistically significant, which speaks to partial mediation effects. On closer inspection, however, this linkage is confined to countries with more unfavorable initial conditions. That is, for these countries the long-run coefficient associated with temperature becomes smaller—in statistically meaningful ways—when the mediators are accounted for, while the same is not true for those countries with more favorable initial conditions. Given that our earlier results suggest that the association between global warming and urbanization is especially relevant to countries with adverse initial conditions, these findings are highly intuitive.[16]

[15] With respect to the latter variable, we make no claims about the quality or scope of public services provided in cities. For instance, McMichael et al. (2012: 650) point out that especially in developing countries urbanization may be accompanied by the expansion of slums or neighborhoods in vulnerable areas in which public goods provision may be rather poor. However, this provision may still be *comparatively* more favorable than public goods provision in rural areas in the same country, providing incentives for rural–urban migration.

[16] In Supplementary Table 8, we also provide a mediation analysis that does not account for the role of unfavorable moderating conditions. Largely consistent with Table 10, this analysis shows that (1) temperature negatively correlates especially with agricultural production and (2) the long-run effect of temperature on urbanization becomes smaller once we control for the mediator variables.

Table 10 Mediation analysis

	(1)	(2)	(3)	(4)
Dependent variable	Agriculture value added	Public goods rural vs. urban	Urbanization	Urbanization
Short-run estimates				
∑ Δ Dependent variable coefficients	−0.141	−0.030	0.889	0.883
	(0.046)***	(0.032)	(0.034)***	(0.035)***
∑ Δ Temperature coefficients when moderator is = 0	0.248	0.001	−0.023	−0.018
	(0.146)*	(0.019)	(0.014)	(0.014)
∑ Δ Temperature coefficients when moderator is = 1	1.495	0.007	−0.023	−0.025
	(0.432)***	(0.009)	(0.012)*	(0.012)**
Long-run estimates				
Error correction	−0.131	−0.055	−0.004	−0.004
	(0.017)***	(0.012)***	(0.001)***	(0.001)***
Long-run temperature effect when moderator is = 0	−0.952	0.060	3.224	2.959
	(0.615)	(0.134)	(1.908)*	(1.732)*
Long-run temperature effect when moderator is = 1	−6.312	−0.190	9.143	6.712
	(1.357)***	(0.115)*	(1.791)***	(1.564)***
[Equality of long-run coefficients within model χ^2-statistic] [$p > \chi^2$]	[15.92] [0.00]**	[4.81] [0.03]**		
[Equality of long-run temperature coefficient between models χ^2-statistic] [$p > \chi^2$]			Moderator is = 0 [0.34] [0.56] Moderator is = 1 [5.25] [0.02]**	
Mediators added?			No	Yes
Further controls	Yes	Yes	Yes	Yes
Within-R^2	0.11	0.05	0.82	0.83
Number of observations	5001	6105	5001	5001

Dynamic fixed-effects estimates reported. Error correction = first lag of respective dependent variable (level-data). Dynamic short-run specification is always l = 1. Further controls = population size; GDP p.c.; democracy. All controls enter all specifications in first-differences and levels in short- and long-run part of model, respectively. The moderator is from the cluster analysis described in the main text (1 = poor starting conditions). Mediators = value added in agriculture and public goods provision equity. Driscoll-Kraay standard errors in parentheses

*$p < 0.1$; **$p < 0.5$; ***$p < 0.01$

6 Conclusion

We analyze the relationship between global warming on rural–urban migration (proxied by the urbanization rate) for a sample of 118 countries between 1960 and 2016. We apply econometric methods that adequately consider various important features of the data such as cross-sectional dependence, non-stationarity and cointegration.

Our findings can be summarized as follows. First, we document a long-run positive relationship between warming and urbanization that is robust to a variety of empirical exercises. Second, this long-run association is especially relevant to countries with more unfavorable initial conditions, i.e., initially non-urban countries that are in hotter climate zones and that are initially poorer, more dependent on agriculture and have institutions that favor their urban centers. This suggests that countries with adverse initial conditions are more likely to be affected because they suffer from lower levels of adaptive capability and higher levels of vulnerability to climate change. Finally, we argue that the positive long-run relationship between temperature and urbanization partly reflects how global warming increases the rural push (by impairing agriculture) and the urban pull (via an increased demand for public goods that are more likely to be supplied in the urban centers), thus incentivizing rural–urban migration especially in the long run. We provide suggestive evidence supporting these transmission channels and associated mediation effects.

Our empirical analysis offers at least three avenues for future research. First, we primarily studied the relationship between increasing temperatures and urbanization, considering other agro-climatic variables only as robustness checks. Future research could investigate the relationship between other weather and climate phenomena (e.g., heat waves, droughts and flood events) and trends in urbanization to more thoroughly capture the role of these phenomena on urbanization in the context of global climate change. Second, while our analysis has already uncovered a number of sources of heterogeneity in the global warming-urbanization nexus, the influence of other factors remains unappreciated. For instance, future research may also examine the roles of democratic institutions, political conflict or international economic integration in explaining heterogeneous effects in the global warming-urbanization nexus. Third, our analysis only allows us to make suggestive claims about the causal nature of the global warming-temperature nexus. That is, a priori our analysis reflects causation either from temperature to urbanization or vice versa, possibly due to the impact of latent (omitted) variables. More research is necessary to identify more clearly causal linkages between temperature and urbanization.

What are the implications of our study? If urbanization contributes to economic growth and development, e.g., via agglomeration benefits or the transfer of agricultural surplus labor from less to more productive economic sectors, the positive association between increasing temperatures and urbanization may be an eventual blessing in disguise. However, there is little evidence of a systematic beneficial effect of urbanization on economic growth (e.g., Bloom et al. 2008). Rather, many developing and emerging countries experience “urbanization without growth” (e.g., Fay and Opal 2000; Bloom et al. 2008), feeling the costs of urbanization without enjoying its benefits. These countries—more likely to be poor, dependent on agriculture and plagued by urban bias—are also the ones where the relationship between global warming and rural–urban migration is most pronounced according to our empirical analysis. For these countries, increasing temperatures may consequently fuel urbanization to a dangerous extent.

The results of our empirical study allow for some policy advice. First, a substantial reduction of greenhouse gas emissions ought to reduce the overall impact of global warming on human life (IPCC 2014), also with respect to its unhealthy interaction with urbanization. Second, to reduce the rural push due to increasing temperatures especially in countries that lack the capacity to absorb rural–urban migration, the vulnerability of rural areas to global warming should be lowered. For instance, this could be achieved by increasing access to public goods (e.g., related to health) in rural areas. Given that the relationship between global warming and urbanization is—according to our empirical results—particularly strong in comparatively poorer economies that may lack the economic and institutional resources to adequately implement adaptive policies, richer countries are well-advised to aid such policy efforts (e.g., by increasing development and technological assistance), not least to moderate international migration (from poor to rich countries) for which urban areas in poorer countries are important hubs.

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Declarations

Conflict of interest The authors declare no competing interests.

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