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# The impact of weather anomalies on migration in sub-Saharan Africa

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ABSTRACT

This paper analyzes the effects of weather anomalies on migration in sub-Saharan Africa. We present a theoretical model that demonstrates how weather anomalies induce rural–urban migration that subsequently triggers international migration. We distinguish two transmission channels, an amenity channel and an economic geography channel. Based on annual, cross-country panel data for sub-Saharan Africa, we present an empirical model that suggests that weather anomalies increased internal and international migration through both channels. We estimate that temperature and rainfall anomalies caused a total net displacement of 5 million people during the period 1960–2000, i.e. a minimum of 128,000 people every year. Based on medium UN population and IPCC climate change projections, we expect future weather anomalies to lead to an additional annual displacement of 11.8 million people by the end of the 21st century.



## 1. Introduction

It is now well-known that local weather anomalies can impose significant strains on economies [93]. A topic that has received much media coverage but little academic research is how exactly incentives migration are shaped by weather anomalies. The number of people that have been forced to leave their homes due to changes in local weather conditions is believed to be anything but negligible. Estimates range from an annual displacement of 15 million environmental refugees[2] during the 1970s [27] to 25 million for the sole year of 1995, of which 18 million originate from Africa [68]. Increasing risks are predicted for the future, with a sea level rise of 1 m potentially producing from 50 million [48] to 200 million environmental migrants [68]. Piguet et al. [77] notes that these estimates[3] were intended to raise awareness but

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[2] The term 'environmental refugee' is itself under discussion. The distinction between refugee and migrant is an important policy debate, notably in terms of assistance and protection, see Black [9], McGregor [59], Kibreab [50] or Suhrke [85]. Throughout the paper, the term 'environmental migrant' will be used. Specifically, in the data, the people crossing a border as a result of environmental damage would not be considered refugees given the mandate to the UNHCR by the 51 Convention of Geneva, but they would be counted as migrants in national statistics.

[3] In its 2010 World Development Report *Development and Climate Change*, the World Bank [93, pp. 108–109], underlines that these "estimates are based on broad assessments of people exposed to increasing risks rather than analyzes of whether exposure will lead them to migrate."

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lack a robust empirical framework and are mostly extrapolations based on the amount of people living in affected regions. Thus, despite the comprehensive overview of the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC), robust evidence regarding the relationship between migration and weather anomalies is still missing [10].

These limitations to the current knowledge of the effect of weather anomalies on migration is regrettable, especially for a topic that is so very much at the heart of the modern, international debate. There exist studies that investigate the environmental motives for rural–urban migration, for example, (e.g. [31,4,44,65,84]), or focus on international migration (e.g. [66,30,69]). While each of these articles provides an important contribution to our understanding of how weather anomalies may drive migration, none studies migration within the comprehensive framework that we offer here.

As we shall argue, rural–urban and national–international migrations are intimately linked and ought to be analyzed within a unified framework. Therefore, it is the objective of this article to provide a theoretical and empirical analysis of the impact of weather anomalies on rural–urban–international migration. Based upon our empirical analysis we also forward a tentative estimate of the number of environmental migrants in Africa between 1960 and 2000, as well as projections of future environmentally driven migration based on UN population forecasts and IPCC future climate scenarios for the end of the 21st century.

There are several stylized facts that a study of rural–urban and urban–international migration should integrate. First, it is well-known that weather anomalies have strong and direct impacts on agricultural activities, whereas manufacturing sectors are less directly affected [47]. Thus, countries that are highly dependent on the agricultural sector are particularly vulnerable to weather anomalies [24,32,93]. Second, as the agricultural sector is predominantly rural, while the manufacturing sector is mostly urban, we should expect migration from rural to urban areas following weather anomalies. Weather anomalies are, therefore, likely to foster urbanization [4,21]. As this internal migration brings more workers to the urban sector, it exerts a downward pressure on the urban wage at home, providing incentives for the internationally mobile workers to move across borders in search of higher wages [41]. Thus, international migration can be seen as a consequence of increasing pressures on the urban areas following rural–urban migration. We dub these wages and urbanization effect the 'economic geography channel'. Third, one should be able to account for the fact that weather anomalies could potentially affect international migration independently of the economic geography channel. Such a direct impact is consistent with studies emphasizing how weather variability may affect amenities [78] or pure non-market costs such as the spread of diseases or a higher probability of death due to flooding or excessive heat waves [93]. Hence, we label this the 'amenity channel'. In line with these stylized facts, our framework encompasses the above channels. Our theoretical model is a continuous time, two-country model with a rural and an urban sector both of which are pricing competitively. Weather anomalies affect the productivity in the rural sector. We allow for rural–urban and urban–international migration, where agents compare their wages in the different sectors and countries when deciding whether to migrate or not. This model predicts that larger weather anomalies induce international migration through rural–urban migration. Furthermore, the more dependent a country is on the agricultural sector, the stronger the impact of weather anomalies on migration.[4]

We collected a new cross-country panel dataset in order to study whether the theoretical results hold in practice. Our focus is on Africa for several reasons. Inhabitants of most sub-Saharan countries already live on the brink of starvation, with more than 60% of people living below the poverty line (see [89]). Furthermore, sub-Saharan Africa disproportionately bears the costs and consequences of global poverty. For example, around 800 million people were at risk of hunger in 2004 [33], leading to approximately four million deaths annually, over half of those in sub-Saharan Africa. Since many African countries rely heavily on agricultural production,[5] even small changes in weather conditions can significantly impact human welfare. Given several scenarios provided by the IPCC [47] that predict increases in temperature and declines in rainfall for most of sub-Saharan Africa, the number of deaths due to adverse weather conditions could easily double in the near future [92]. In light of the high vulnerability of sub-Saharan Africa to weather anomalies and the IPCC projections, it is useful to identify the role that weather conditions play in the determinants of migration in sub-Saharan Africa. Hatton and Williamson [41] are among the first to have conducted an empirical analysis on the determinants of international migration in Africa. Their study underlines the importance of the wage gap between sending and receiving regions as well as demographic booms for explaining net migration. While taking into account economic and political determinants of migration, they do not account for the potential environmental push factor that may be important in determining African migration. Addressing this gap, Barrios et al. [4] find that weather conditions in sub-Saharan Africa lead to a displacement of people internally. However, our theoretical model hints at further effects from weather anomalies, namely that also changes in urban centers and relative wages provide motivation for international migration. For example, increased urbanization is likely to mitigate the impact of weather on international migration due to agglomeration forces. One of our motivations, therefore, is to understand the importance of this economic geography effect channel on migration in sub-Saharan Africa.

Though most previous studies proxy weather anomalies by rainfall (e.g. [4,5]), weather anomalies in sub-Saharan Africa are also significantly related to increases in temperature. Even small changes in temperature can dictate whether a region

[4] For a North–South overlapping generations model that does not take the link between rural–urban migration into account but studies inequality and policy solutions we refer the reader to Marchiori and Schumacher [55].

[5] In several countries up to 90% of the population works in the agricultural sector, see [33].

is semi-arid like Italy or arid like Namibia. Dell et al. [23] show that the detrimental impact of weather anomalies on economic performances is mainly driven by annual variations in temperature. Therefore, our aim here is to look specifically at both temperature and rainfall anomalies, which provides a fairly complete picture of the true extent of weather anomalies [47].

Guided by the theoretical model, we study the economic geography channel of weather anomalies on wages and urbanization, both of which the theoretical model predicts to be the main variables driving international migration decisions. We find that weather anomalies are, especially for agriculturally dominated countries, an important determinant of international migration over the period 1960–2000. We interpret the empirical results in light of the theoretical model as follows. We find that larger weather anomalies lead to a lower rural wage. This induces migration into the cities since cities are generally not directly (or not as severely as rural areas) affected by weather anomalies. We find evidence supporting that urbanization induces in-migration through positive agglomeration externalities. However, the reduction in the wages outweighs the benefits of urban concentrations (or agglomeration forces) and, therefore, weather anomalies induce out-migration. Based on these empirical results we then estimate that a minimum of approximately 5 million people have migrated internationally due to variations in local weather in sub-Saharan Africa between 1960 and 2000. This represents 0.3 per thousand individuals or 128,000 people every year. We then project the impact of weather anomalies on the future rates of migration in sub-Saharan Africa based on the moderate IPCC climate scenario A1B (see Section 3.5 for details). Our projections suggest that, in sub-Saharan Africa towards the end of the 21st century, every year an additional 1.21, 3.4 and 5.32 per thousand individuals in sub-Sahara Africa will migrate in the best, median and worst weather forecasts of IPCC scenario A1B. Multiplied by the medium-fertility UN population projection for the end of the century, this would amount, every year, to an additional displacement of 4, 11.8 and 18.5 million inhabitants in the best, median and worst weather forecasts of the IPCC climate scenario.

This paper is organized as follows. Section 2 introduces the theoretical framework. Section 3 presents the data, methodology and the empirical results of our study. Section 4 concludes.

## 2. A theoretical framework

In this section, we introduce a simple theoretical model that helps to motivate the modeling choices in the subsequent empirical analysis. The model is used as a roadmap for understanding the impact of weather anomalies on migration flows by exposing the link from weather anomalies to rural–urban and urban–international migration, allowing for the amenity as well as the economic geography channel.

In the following framework, a change in any variable $x_t$ over time is denoted by $\dot{x}_t$; the derivative is denoted by a subscript. We assume that there exists a mass 1 of nationally mobile workers that work in the rural sector or in the urban one. These workers are thus mobile across sectors only. A share $L_t \in [0,1]$ of these nationally mobile workers works in the urban sector, while $1-L_t$ work in the rural sector. There are $N_t \in [0,1]$ internationally mobile workers that only work in the urban sector but are mobile across countries. Hence, we assume two sectors, the rural sector with production technology $Y^a(c,1-L_t)$, where $c$ denotes weather, and the urban sector with $Y^u(N_t+L_t,N_t)$. Both productions exploit decreasing returns to scale in labor.[6]

Weather is assumed to affect total productivity in the rural sector. One would ideally want to measure weather through a random variable, say $z$, with support $z \in [0,\infty]$. Zero would then represent the best outcome while infinity would designate the worst. On average we would expect the outcome $E(z) = \int_0^\infty zf(z)\,dz$, with $f(z)$ denoting the probability function. In order to allow for a concise and precise theoretical analysis, and without an important loss of generality, we shall avoid modeling weather as a stochastic process here. Hence, we simply denote a random draw from the distribution $f(z)$ as $c>0$. On average, we would thus expect that $c=E(z)$, while a year with a worse outcome would imply $c>E(z)$.[7]

We take capital and knowledge as given and encompassed in the total factor productivities. Both the rural and urban sectors price competitively; prices in each sector are given. The rural sector produces according to $w^a(1-L_t,c) = p^a Y^a_{1-L}$, with $w^a_{1-L}<0$, $w^a_c<0$ and $\lim_{L\to 1} w^a = \infty$. The optimal wage in the urban sector is given by $w^u(L_t+N_t,N_t) = p^u Y^u_L$, with $w^u_L<0$, $w^u_N<0$. While the first part of $w^u$ reflects the total number of workers active in the urban sector, the second part stands for a Marshallian externality on productivity that arises from labor sharing, input–output linkages or information [26]. It represents agglomeration effects.[8] Workers compare their wages across sectors and countries and migrate if they can obtain higher wages elsewhere. Within this framework, nationally mobile workers then decide to move from the rural

[6] Our assumption of decreasing returns to scale in agricultural production could be questioned on the grounds of the replication argument. An obvious remedy in this case is to assume the existence of another factor of production like land $X$, that is constant, non-tradeable and unpriced, such that $Y^a = Y^a(c,1-L_t,X)$, with $Y^a$ now being homogeneous of degree 1 in land and labor. This would preserve the results presented above. One could even go one step further and assume that the new factor of production earns a return itself, but that this return is the residual profit from production. In any case, the decreasing returns to scale in labor are a crucial assumption that cannot be dispensed with if one wants the model to have an interior solution.

[7] In this way we also avoid the analytics associated with a system of stochastic differential equations and a stochastic steady state. Though mathematically feasible, we would not learn more about migration dynamics by going through such an exercise.

[8] Functional forms consistent with these assumptions are, e.g., $Y^a = A(c)(1-L_t)^\alpha$, $\alpha \in (0,1)$, $A(c)>0$ with $A'(c)<0$, where $A$ denotes the total factor productivity in the rural sector that is negatively affected by weather anomalies, represented by $c>0$. Also, $Y^u = B(N_t)(L_t+N_t)^\beta$, where $B_N>0$ is the marginal effect of $N$ on the Marshallian externality, $\beta \in (0,1)$ is the elasticity of labor.

to the urban region according to

$$\dot{L}_t = w^u(L_t+N_t,N_t)-w^a(1-L_t,c). \tag{1}$$

Thus, the number of nationally mobile workers that work in the urban sector increases if the wage in the urban sector is higher than in the rural one.

As for international migration, we assume that internationally mobile workers compare their wage at home with the wage of the country to which they intend to migrate, denoted by $w^*(1-N_t)$. The final term is a direct weather effect, given by $g(c)$, with $g_c > 0$.

We assume that workers who migrate have a negative impact on the other country's wage, such that $w^*_{1-N} < 0$. The term $g(c)$ assumes that weather anomalies also have a direct impact on internationally mobile workers through a change in the amenity value of the weather at home. It should capture what we dubbed the amenity channel. For sub-Saharan Africa, we expect such amenities to reflect important non-market costs induced by weather anomalies such as poor environmental quality, possible spread of diseases like malaria, dengue or meningitis and consequently increasing morbidity and mortality [93].

Thus, workers from the urban region migrate internationally according to

$$\dot{N}_t = w^u(L_t+N_t,N_t)-w^*(1-N_t)-g(c). \tag{2}$$

As such, internationally mobile workers migrate if the net international wage exceeds the wage they would otherwise obtain in the urban sector at home or if the amenity channel is very strong. For simplicity, the subscript $t$ is dropped in the equations that follow.

**Assumption 1.** We assume that (1) $\lim_{L\to 0} w^a(1-L,c) < w^*(1-N)+g(c)$; (2) $w^u(L,0) > w^*(1)+g(c)$; and (3) $w^u(L+1,1) < w^*(0)+g(c)$.

The first part of this assumption means that, if all nationally mobile workers were to stay in the rural sector, then the international wage must be higher than the rural wage. If it were lower, then there would be no reason for moving into the urban sector and we would see a corner solution in $L$ . The second and third parts of the assumption simply require the national wage to be sufficiently responsive to international migration. All three conditions are weak and straight-forward.

We are now ready to study this rather intuitive model of weather anomalies inducing rural–urban and urban–international migration.

**Proposition 1.** *At equilibrium, a larger weather anomaly induces international migration directly and indirectly via rural-to-urban migration.*

**Proof.** We assume that $\dot{N} = \dot{L} = 0$. Combining Eq. (1) with Eq. (2) gives the equilibrium condition $w^*(1-N)+g(c) = w^a(1-L,c)$. Since $w^*(1-N)+g(c) > 0$, by Assumption 1 and $\lim_{L\to 1} w^a = \infty$, then there exists an interior solution in $L$. Taking the interior solution of $L$ as given, Assumption 1 also assures an interior solution in $N$. Deriving the weather anomalies' impact on the equilibrium locational decisions gives us

$$\frac{dL}{dc} = \frac{w^a_c(w^u_N + w^*_{1-N}) - g_c w^u_N}{w^u_N w^a_{1-L} + w^*_{1-N}(w^u_L + w^a_{1-L})} > 0, \tag{3}$$

$$\frac{dN}{dc} = \frac{g_c}{w^u_N + w^*_{1-N}} - \frac{w^u_L}{w^u_N + w^*_{1-N}}\frac{dL}{dc} < 0. \tag{4}$$

Hence, the proposition follows. □

Thus, weather anomalies increase rural-to-urban migration as well as urban-to-international migration. Additionally, a stronger amenity effect induces greater international migration directly, which increases the wage in the urban sector at home and therefore gives further incentives for rural–urban migration. The larger the effect of weather anomalies in the rural sector the more pronounced will be the rural–urban migration and the larger will be the international migration.

The next proposition derives the equilibrium dynamics of this model.

**Proposition 2.** *The system of Eqs.* (1) *and* (2) *has an asymptotically stable equilibrium point* $\{\overline{L},\overline{N}\}$.

**Proof.** By Proposition 1 we know that there exists an interior equilibrium solution in $L$ and $N$ that we denote as $\{\overline{L},\overline{N}\}$, where $\{\overline{L},\overline{N}\}$ solves $\dot{N} = 0$ and $\dot{L} = 0$. We derive the Jacobian around the steady state $\{\overline{L},\overline{N}\}$. This is given by

$$\mathcal{J}|_{(\overline{L},\overline{N})} = \begin{bmatrix} w^u_L + w^a_{1-L} & w^u_N \\ w^u_L & w^u_N + w^*_{1-N} \end{bmatrix},$$

The trace is $\mathrm{tr}\mathcal{J} = w^u_L + w^a_{1-L} + w^u_N + w^*_{1-N} < 0$ and the determinant is $\det\mathcal{J} = w^u_N w^*_{1-N} + w^a_{1-L}(w^u_N + w^*_{1-N}) > 0$. Since the eigenvalues are given by

$$\lambda_{1,2} = \tfrac{1}{2}\left(\mathrm{tr}\mathcal{J} \pm \sqrt{(\mathrm{tr}\mathcal{J})^2 - 4\det\mathcal{J}}\right),$$

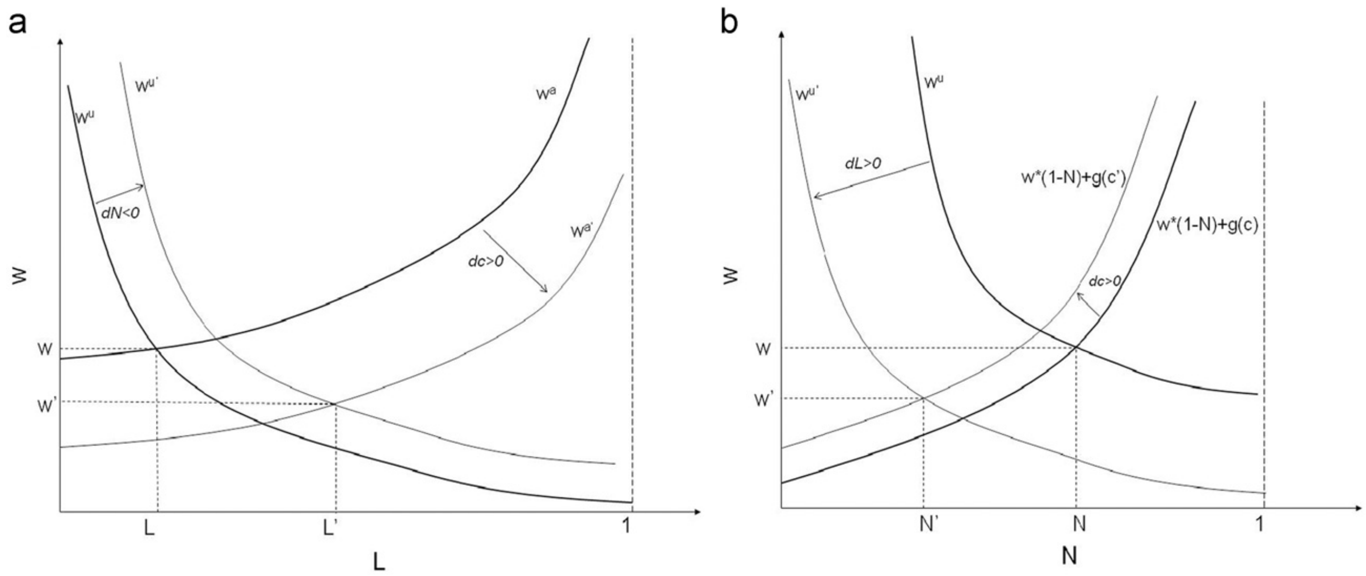


**Fig. 1.** Rural–urban and international migration. (a) Rural sector. (b) Urban sector.

we know that both eigenvalues are either negative or complex with negative real part. Thus, the equilibrium point $\{\overline{L},\overline{N}\}$ is asymptotically stable. Disregarding complex dynamics for simplicity, this implies that $\lambda_1 < 0$ and $\lambda_2 < 0$. □

Consequently, we know that, given a change in the weather conditions, both $L$ and $N$ will converge to a unique, interior steady state.

The storyline that we suggest here captures what we believe to be the most reasonable underlying processes for weather-induced migration decisions. Fig. 1 illustrates the migration mechanisms graphically. Assume we are at the equilibrium point $\{L,N\}$, and now the weather condition in the sending country worsens, such that $dc > 0$. This has two immediate effects. First, the wage in the rural sector shrinks, thus shifting the $w^a$ curve down. This brings forth incentives for rural–urban migration. At the same time, there is a direct effect from the amenity value of the environment which induces incentives for urban–international migration. In addition, due to the inflow of nationally mobile workers from the rural into the urban sector, the wage in the urban sector decreases (per unit of $N$), and therefore the curve $w^u$ shifts down. This gives further incentives for urban–international migration. Due to the Marshallian externality, this effect is not as pronounced as it otherwise would be. International factor price equalization is then achieved via two channels. International migration has a positive effect on the international wage via agglomeration forces and a negative one via decreasing returns to scale to labor. Conversely, the urban wage will increase, as shown by the shift of the $w^u$ curve in the left panel. Given assumption 2, the latter effect will dominate the former, leading to a decrease in the foreign country's wage. We thus arrive at a new equilibrium point that is given by $\{L',N'\}$.

Furthermore, simple comparative statics suggest that a stronger agglomeration effect would flatten the curve $w^u$ and thereby diminish the change in international wages. Without the direct effect of the amenity value of weather, the curve $w^*(1-N)+g(c)$ would not shift up and therefore international migration would be lower. Similarly, with little international migration, the curve $w^u$ in the left part of Fig. 1 would shift up by less, the effect being a lower amount of sectoral migration.[9]

To complete the analysis we now derive the effect of weather anomalies on several variables that give us crucial hints for the way we should set up the empirical analysis.

We first derive the effect of weather anomalies on urbanization. We here define urbanization as $\psi = (L+N)/(1+N)$.

**Proposition 3.** *Weather anomalies increase equilibrium urbanization if the amenity channel is weak enough and agglomeration forces are sufficiently small.*

**Proof.** Since urbanization is defined as $\psi = (L+N)/(1+N)$, we can easily calculate

$$\frac{d\psi}{dc} = \frac{1+N}{(1+N)^2}\frac{dL}{dc} + \frac{1-L}{(1+N)^2}\frac{dN}{dc}.$$

[9] The direction of the changes presented here rests crucially on the assumption that $w^u_N < 0$. If agglomeration forces were stronger than the diminishing returns to labor in production, then some effects could be reversed. However, it seems rather natural for us to assume that wages are more responsive to migration than to agglomeration effects. We confirm this in the subsequent empirical analysis.

Substituting for $dN/dc$, assuming $g_c \to 0$, gives

$$\frac{d\psi}{dc} = \frac{1}{(1+N)^2}\frac{(1+N)(w_N^u + w_{1-N}^*) - (1-L)w_L^u}{w_N^u + w_{1-N}^*}\frac{dL}{dc}.$$

Then $(1+N)(w_N^u + w_{1-N}^*) - (1-L)w_L^u < 0$ implies $d\psi/dc > 0$. □

This result may be explained as follows. Since weather anomalies induce rural–urban migration, then the subsequent decrease in the urban wage will induce international migration. As a consequence, we see an increase in urbanization, since both the number of inhabitants and the number of nationally mobile workers in the rural sector decrease. This holds unless the amenity effect of $g(c)$ is too strong or if the residual of $w_N^u - w_L^u$, representing the effect of $N$ on the agglomeration externality, is too large.

The next proposition derives the amenity channel.

**Proposition 4.** *A stronger amenity channel leads to out-migration.*

**Proof.** The amenity effect is given by the effect of $g(c)$ on $N$ only. By Eq. (4), this effect is negative. □

Therefore, the stronger the effect of weather anomalies on the amenity value at home, the more will internationally mobile workers be inclined to migrate abroad. We dub this the amenity channel since it explains how weather anomalies affect migration directly without going through other variables like urbanization or wages.

Our final proposition is related to a country's exposure to weather anomalies. We define a country that is dependent on one sector as one where that sector produces a relatively larger share of GDP.

**Proposition 5.** *The more dependent a country is on the rural sector, the stronger the impact of weather anomalies on migration.*

**Proof.** From the profit functions we know that a higher $c$ implies a lower $Y^a$ versus $Y^u$. Furthermore, from Eq. (3) we know that $L$ at steady state is increasing in $c$. From Eq. (4), the proposition thus follows. □

This result seems rather intuitive. The impact of weather anomalies will be greater in countries whose economies are more exposed to those anomalies. Specifically, this exposure term might be very low for more urbanized countries with larger manufacturing sectors and production mostly independent of weather anomalies. Exposure will be greater for countries that are very dependent on the agricultural sector. In such countries, even small changes in weather conditions might lead to significant impacts.

This framework abstracts from several aspects. For example, it has been established that migrants move with their demand and can affect consumer prices [83,53] as well as the profitability of locally provided goods and services. In addition, migrants can also constitute complementary factors of production in the migrant-receiving countries and strengthen agglomeration economies [76]. We did not allow for changes in prices and neither for (costly) trade in goods or firm re-allocations, and we introduced agglomeration effects as well as consumer surplus considerations in a somewhat stylized way. In addition, no moving cost has been introduced in the migration decision. A final caveat is that the model does not account for the size of the migrant-sending economy. In the case that the sending country has a small economy, one would expect the receiving country's wage to be unresponsive to migration from that country, such that $w^* = \overline{w}^*$. Though this does not qualitatively change the results presented above, we are likely to see a larger rural–urban and a larger international migration from the small country. This increase is due to the fact that, in this case, international migration does not drive down the receiving country's wage. Consequently, more international migration is necessary to restore equilibrium. Nevertheless, we believe that the model captures the crucial qualitative links of rural–urban and urban–international migration.

## 3. Empirical analysis

Since Todaro's [87] seminal paper and the review by Yap [94], it has become standard in the literature to relate, in an aggregate form, the migration rate to changes in expected income and to changes in the degree of urbanization (see also [86]). We will not depart from this tradition. However, Propositions 1, 3 and 4 of our theoretical framework not only point to the importance of the amenity channel but also to the economic geography (via income and urbanization) channel through which weather anomalies could affect international migration. The theoretical model and its discussion also shed light on possible risks of endogeneity. As discussed above, the self-reinforcing and cumulative nature of migration makes economic wealth and the level of urbanization potentially endogenous variables. Therefore, we develop a three-equation model, with one equation for the net migration rate, one for GDP per capita and one for the level of urbanization. We collect a new dataset of 39 sub-Saharan African countries with yearly data from 1960 to 2000. This cross-country panel data consists of migration variables, variables describing the weather characteristics, economic and demographic variables, and several country-specific variables. The country list can be found in Appendix Table 1. Our three-equation model is

**Table 1**
Countries.

| Regions | Countries |
|---|---|
| **Central** | Burundi, Cameroon, Central African Republic, Chad, Congo Brazzaville, Congo Kinshasa, Gabon, Rwanda |
| **East** | Djibouti, Ethiopia, Kenya, Mauritius, Sudan, Tanzania, Uganda |
| **South** | Angola, Botswana, Lesotho, Malawi, Mozambique, Namibia, Swaziland, Zambia, Zimbabwe |
| **West** | Benin, Burkina Faso, Côte d'Ivoire, Gambia, Ghana, Guinea, Guinea Bissau, Liberia, Mali, Mauritania, Niger, Nigeria, Senegal, Sierra Leone, Togo |

formulated as follows:

$$\mathrm{MIGR}_{r,t} = \beta_0 + \beta_1 \mathrm{WeatherA}_{r,t} + \beta_2(\mathrm{WeatherA}_{r,t} * \mathrm{AGRI}_r) + \beta_3 \log\left(\frac{\widehat{\mathrm{GDPpc}}_{r,t}}{\mathrm{GDPpc}_{-r,t}}\right) + \beta_4 \log(\widehat{\mathrm{URB}}_{r,t}) + \beta_X \mathrm{X}_{r,t} + \beta_{R,t} + \beta_r + \epsilon_{r,t} \tag{5}$$

$$\log\left(\frac{\mathrm{GDPpc}_{r,t}}{\mathrm{GDPpc}_{-r,t}}\right) = \gamma_0 + \gamma_1 \mathrm{WeatherA}_{r,t} + \gamma_2 (\mathrm{WeatherA}_{r,t} * \mathrm{AGRI}_r) + \gamma_X \mathrm{X}_{r,t} + \gamma_Z \mathrm{Z}_{r,t} + \gamma_{R,t} + \gamma_r + \mu_{r,t} \tag{6}$$

$$\log(\mathrm{URB}_{r,t}) = \theta_0 + \theta_1 \mathrm{WeatherA}_{r,t} + \theta_2(\mathrm{WeatherA}_{r,t} * \mathrm{AGRI}_r) + \theta_X \mathrm{X}_{r,t} + \theta_Z \mathrm{Z}_{r,t} + \theta_{R,t} + \theta_r + \nu_{r,t} \tag{7}$$

This baseline model suggests that $\mathrm{MIGR}_{r,t}$, which represents average net migration rates, can be explained by a set of weather variables (weather anomalies, defined below) $\mathrm{WeatherA}_{r,t}$; by per capita GDP ($\mathrm{GDPpc}_{r,t}$) as a proxy for the domestic wage; by the foreign per capita GDP, i.e. average per capita GDP in the other SSA countries weighted by the distance to country $r$ ($\mathrm{GDPpc}_{-r,t}$); by the share of the urban population ($\mathrm{URB}_{r,t}$) as well as by a vector of control variables ($X_{r,t}$), described below. $Z_{r,t}$ is a set of instrumental variables discussed in Section 3.2.

As suggested by Propositions 1 and 3, we allow weather anomalies to affect international migration through the economic geography channel, which works its way through per capita GDP and the level of urbanization. Proposition 5 also invites us to assess the differentiated impact of weather variables in countries whose economies largely depend on the agricultural sector. We introduce, therefore, the interaction terms ($\mathrm{WeatherA}_{r,t} * \mathrm{AGRI}_r$), where $AGRI_r$ is an "agricultural" dummy, which, as in Dell et al. [23], equals 1 for an above median agricultural GDP share in 1995.[10] Denoting $\alpha \in \{\beta, \gamma, \theta\}$, we also control for any time-constant source of country heterogeneity by the use of country fixed effects $\alpha_r$ and for phenomena common to all countries across time through the introduction of time dummies $\alpha_t$. We also follow Dell et al. [23] in introducing a time-region fixed effect, $\alpha_{R,t}$, thus controlling for the importance of changes in the regional migration patterns in sub-Saharan Africa [1].

### 3.1. *Description of variables*

To compute the variables introduced in the system of equations above, data are collected from several sources. Descriptive statistics are provided in Tables 2 and 3 (Table 1 in Supplementary Material offers a detailed description with data sources for the different variables. Supplementary Material can be found at http://aere.org/journals.).

- $MIGR_{r,t}$: The *net migration rate* is defined as the difference between immigrants and emigrants per thousands of population, corrected by net refugee flows (see below). Typically, research on international migration uses bilateral data on migration flows or stocks to analyze migration into developed countries. However, such data is barely available for developing countries and particularly difficult to obtain for Africa (over a longer period) because cross-border migration in sub-Saharan Africa is poorly documented [95].[11] Thus, we do not use directly observable data for international migration. Like Hatton and Williamson [41], we rely on net migration flow as a proxy for cross-border migration. This data is available for the period 1960–2000 and provided by the US Census Bureau. It is constructed from a combination of directly observable international migration data based on official population registers and indirect observations, i.e. migration estimates using a variety of sources, including censuses, surveys, and administrative

[10] We follow Dell et al. [23, footnote 10] in using 1995 data for agricultural share because data coverage for earlier years is sparse.

[11] Directly observable cross-border migration data for Africa can be found in the United Nations Demographic Yearbooks and in the ILO's International Migration Database, but the number of entries is very scarce. In order to deal with the lack of bilateral migration data and to control for possible spatial dependency introduced by such data constraint, we exploit spatial weighting matrices in order to capture the influence of some variables in neighboring countries. In line with the seminal work of Ravenstein [80] on the role of distance in migration flows, such a weighting also constitutes a way to take into account the costs of migration across borders, which should be positively correlated with distance [20].

**Table 2**
Short description of main variables.

| CODE | Definition/description |
|---|---|
| MIGR | Net migration rate: difference between numbers of immigrants and emigrants per thousands of population, corrected by the refugee movement |
| RAIN | Rain anomalies, deviations from the country's long-term mean, divided by its long-run standard deviation |
| TEMP | Temperature anomalies: deviations from the country's long-term mean, divided by its long-run standard deviation |
| $y/y^F$ | GDP per capita over GDP per capita in other African countries weighted by distance |
| WAR | War onset, value 1 for civil war onset |
| $WAR^F$ | War onsets in other countries weighted by distance |
| URB | Share of urban population in total population |
| AGRI | Whether a country has an agricultural value added above the median in 1995 (similar to Dell et al. [23]) |
| ΔMoney | Money plus Quasi-Money: absolute growth in money supply |
| New State | Independence: value 1 if country is in the two first years of independence |
| $MIGR^a$ | Original net migration rate, without refugee movement correction |
| NetREF | Net refugee movement per thousands of population |

A more detailed description of variables containing the different sources for the data is provided in Supplementary Material.

**Table 3**
Descriptive statistics.

| Variable | Mean | Std. dev | Units |
|---|---|---|---|
| MIGR | 0.1511 | 20.657 | per 1000 of population |
| $MIGR^a$ | 0.1581 | 8.930 | per 1000 of population |
| $RAIN_{level}$ | 1051.2470 | 578.741 | mm |
| $TEMP_{level}$ | 24.4440 | 3.371 | °C |
| RAIN | −0.3688 | 0.975 | Anomalies |
| TEMP | 0.5588 | 1.063 | Anomalies |
| AGRI | 0.4347 | 0.496 | 1 if country's agricultural share of GDP is above median in 1995, 0 otherwise |
| RAIN*AGRI | −0.1583 | 0.648 | |
| TEMP*AGRI | 0.2221 | 0.754 | |
| $WAR_{t-1}$ | 0.0333 | 0.180 | 1 if more than 100 deaths, 0 otherwise |
| $WAR^F_{t-1}$ | 0.0298 | 0.059 | |
| URB | 28.5612 | 14.725 | % of population |
| (log)URB | 3.1931 | 0.616 | |
| $\log(y/y^F)$ | −1.1689 | 0.836 | |
| ΔMoney supply | 0.0277 | 0.140 | In $10^{12}$ US dollars |
| New state | 0.0053 | 0.073 | 1 if country is in 2 first years of independence, 0 otherwise |
| New state UK | 0.0040 | 0.063 | 1 if country is in 2 first years of independence from UK, 0 otherwise |
| NetREF | $-6.69\times10^{-5}$ | 18.528 | per 1000 of population |

$MIGR^a$ stands for net migration rate without the correction for the refugee movement. $t-1$ indicates a one period lagged variable.

records.[12] Moreover, like Hatton and Williamson [41], we account for refugees who are driven by non-economic factors and who are included in the net migration estimates. To do so, we subtract the refugee movement from the net migration rate. The US Census includes net refugee movement in its net migration series by using UNHCR refugee data. Using the same source [88], we compute the *net* refugee movement (NetREF), which is expressed per thousand of the country's population, as the difference between the change in the stock of refugees living in a country (change in refugees residing in country $r$) and the change in the stock of refugees from that country living elsewhere (change in refugees originating from country $r$). Our robustness analysis reveals that our main findings are not sensitive to this correction (see Section 3.4).

- $WeatherA_{r,t}$: *Weather variables* should capture the incentives for migration that come through weather anomalies. In line with the climatology literature (see for example, [70,71,67]), we use anomalies in precipitations and in

[12] The US Census Bureau's strategy to construct its migration data series can be summarized as follows. First, the US Census Bureau uses direct net international migration observations from country censuses on foreign born population or data from general sources such as Eurostat, the International Labor Organization (ILO), International Organization for Migration (IOM), the Organization for Economic Cooperation and Development (OECD). Net migration can be estimated for the intercensal period from census data, especially when it contains information such as place of birth of the foreign-born population or date of arrival and departure. Second, when no or few direct migration observations are available, the US Census relies on indirect estimation techniques, which are applied through an iterative process to generate the most accurate results possible [91, pp. 22–26]. For instance, the census cohort analysis attributes irregularities in the comparison of population by year of birth across two or more censuses to net migration. The residual technique calculates net migration as the differences between observed census population distribution and population distribution resulting from a population projection that accounts for natural population growth but not migration [91, pp. 22–26]. The residual technique is more likely than the direct, observational approach to include illegal and undocumented migrants.

temperature. The anomalies are computed as the deviations from the country's long-term mean, divided by its long-run standard deviation. Rainfall and temperature data originate from the IPCC [63]. Like Barrios et al. [5], we take the long-run to be the 1901–2000 period and denote the weather anomaly WeatherA, which represents either rainfall anomaly (RAIN) or temperature anomaly (TEMP), as follows:

$$\text{WeatherA}_{r,t} = \frac{\text{WeatherA}_{level,r,t} - \mu_r^{LR}(\text{WeatherA}_{level})}{\sigma_r^{LR}(\text{WeatherA}_{level})} \tag{8}$$

where $\text{WeatherA}_{level,r,t}$ stands for the level of either rainfall or temperature of country $r$ in year $t$, and $\mu_r^{LR}(\text{WeatherA}_{level})$ and $\sigma_r^{LR}(\text{WeatherA}_{level})$ are country $r$'s mean value and standard deviation, respectively, in rainfall or temperature over the long-run (LR) reference period. As pointed out by Barrios et al. [5], anomalies allow one to eliminate possible scale effects and take account of the likelihood that for the more arid countries variability is large compared to the mean [67]. The long-term mean gives an idea of the 'normal' weather conditions of a particular region. Anomalies thus describe how far weather conditions depart from this norm in a given year.[13]

- $GDPpc_{r,t}$: *GDP per capita* is used as a proxy for the domestic wage. A comparison with the 'foreign' wage should reflect an individual's economic incentives to migrate. In the tables we use the notation $y$ for this variable. One challenge of directly translating the theoretical framework into an empirical one is that we do not have separate data on rural and urban wages. However, we do not consider this a serious problem for the following reasons. According to our theoretical framework, weather anomalies will impact the rural wage and drive urban wages in the same direction. That is, whenever weather anomalies reduce rural wages, they also drive down urban wages, implying a reduction in the domestic average wage, which is adequately proxied by GDP per capita. Furthermore, the more easily migrants can move between rural and urban areas the more the wage differential between both areas will be minimized.
- $GDPpc_{-r,t}$: *Foreign GDP per capita* proxies the 'foreign' wage, i.e. the wage outside the home country, and is measured as average GDP per capita in the other countries of the sample weighted by a distance function $\sum_{s=1}^{N} f(d_{r,s}) wage_{s,t}$, where $f(d_{r,s}) = 1/(d_{r,s})^2$.[14] In the tables we use the notation $y^F$ for this variable.
- $URB_{r,t}$: *Urban population* is defined as the ratio of urban to total population in each country and originates from the United Nations [90].
- $X_{r,t}$: Our baseline regression includes a set of *control variables*. The occurrence of war seeks to capture the political motivations to migrate. Data on the number of internal armed *conflicts* (*WAR*) are used. This is particularly relevant in the case of Africa where internal conflict has been by far the dominant form of conflict since the late 1950s [37]. We expect a negative sign, as war should lead to out-migration. Forced migration is undeniably an important feature of migration in Africa. Between the early 1980s and the mid 1990s, Africa hosted 30–45% of the world total refugee stock. The number of refugees in Africa increased from 1960 to 1995, but due to resolution of conflicts, important repatriations were made possible beginning in the 1990s. Nevertheless, refugees accounted for a large share of the total migrant *stock* in Africa rising from 25% in 1980, to 33% in 1990 and declining to 22% in 2000 [96].[15] We also follow Hatton and Williamson [41] in introducing four country-specific policy dummies. For example, Hatton and Williamson [41] suggest controlling for the large expulsion of Ghanaian migrants by the Nigerian government in 1983 and 1985.
- *Time-regional dummies* are introduced using the grouping described in Table 1. Use of these time-regional dummies should capture the regional pattern of migration underlined by several authors. In fact, cross-border migration in sub-Saharan African is not distributed evenly across regions. In 2000, 42% of the international migrants in Africa lived in Western Africa, 28% in Eastern Africa, 12% in Northern Africa, and 9% in Central and Southern Africa each [95, p. 5]. Moreover, trans-boundary migration often occurs among countries of the same region as these regions each have their own attraction poles and economic grouping, e.g. the Economic Community of West Africa States, the Southern African Development Community and the Common Market of East and Southern Africa [1]. For example, surveys of the population aged 15 years and older showed that, in 1993, 92% of all the foreigners in Ivory Coast—a main attraction pole for migrants in the region—originated from seven other Western African countries [95].

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[13] Since the anomaly transformation provides a partial correction to year-to-year fluctuations, the reader should keep in mind that we are capturing deviations in the weather from the norm.

[14] Although Head and Mayer [42] warn against giving a structural estimation to this proxy, the 'foreign' wage could be interpreted as the Real Market Potential introduced by Harris [40]. It is unfortunately not possible to proceed to Redding and Venables [81] estimation of the real market potential on the investigated period, given the lack of bilateral trade data availability before 1993 [11]. We use distance data from the CEPII [57], and more specifically the simple distance calculated following the great circle formula, which uses latitudes and longitudes of the most important city (in terms of population). The Foreign GDP per capita is therefore constructed by making the less restrictive assumption regarding migration costs, i.e. increasing linearly with distance. As indicated in Section 3.4., our results are nonetheless robust to alternative proxies for migration barriers, including colonial link, contiguity, common colonial ruler and linguistic proximity.

[15] Given the fact that migration data incorporate refugee figures, we do not follow Hatton and Williamson [41] in introducing net numbers of refugee flows as an explanatory variable. This would generate an obvious endogeneity problem due to the simultaneity between this additional variable and the dependent variable. We prefer to subtract the net refugee flows directly from our dependent variable. Still, we will show that results are not fundamentally changed when we follow Hatton and Williamson's [41] approach. Our estimation also differs from that of Hatton and Williamson [41] in the sense that we include a country fixed effect while their paper uses a Pooled Ordinary Least Squares (POLS) estimation. An *F*-test unambiguously confirms the presence of unobserved fixed effects and the Hausman test unambiguously supports the use of a fixed effect model over a random effect one.

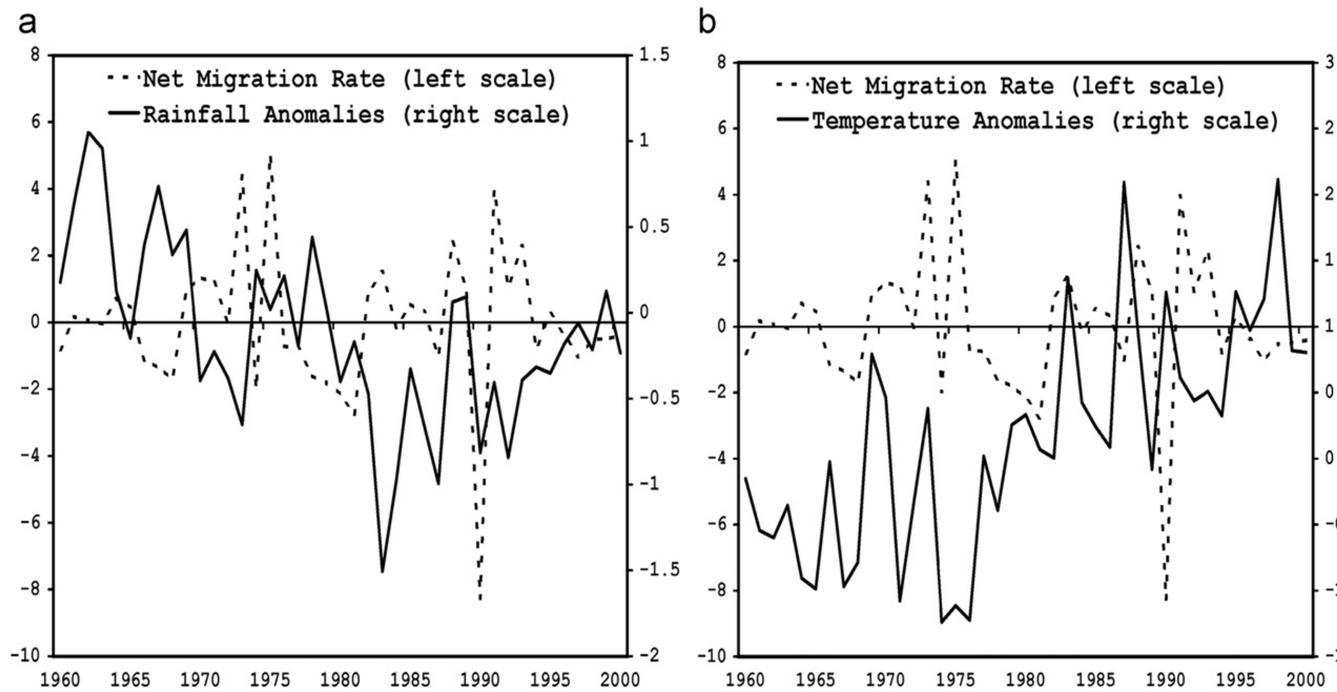


**Fig. 2.** Weather anomalies and net migration rate in sub-Saharan Africa. (a) Rainfall and net migration. (b) Temperature and net migration. *Source*: IPPC for rainfall and temperature data and US Census for net migration.

Fig. 2a and b plot net migration rate against rainfall and temperature anomalies, respectively, for the 39 sub-Saharan African countries of the sample over the period 1960–2000. Temperature is increasing whereas rainfall is decreasing across time, indicating that sub-Saharan Africa is experiencing weather changes over the period of our investigation. Moreover, Barrios et al. [4] stress that rainfall in sub-Saharan Africa remained constant during the first part of the 20th century until the 1950s, peaking in the late 1950s and following a clear downward trend since that peak. However, while the weather variables indicate clear trends, the average net migration variable does not. Thus, judging by on correlation alone, it is difficult to state whether the net migration rate and rainfall/temperature anomalies move together. Furthermore, our identification strategy exploits year-to-year anomalies of temperature and rainfall anomalies *within* countries that cannot be observed in the averaged series of Fig. 2a and b.

Given the relatively long time period used, the non-stationary nature of our variables may be a point of concern, as they may lead to possibly spurious relationships [54]. To address this concern, we perform the Fisher panel data unit root test on the dependent and the explanatory variables (see Table 2 in Supplementary Material). The tests show that all series are stationary at any reasonable level of confidence.

### *3.2. Dealing with endogeneity*

Despite the introduction of region-time dummies which are likely to capture some time-specific and time-region-specific events, we might fail to account for an unobserved effect that is both country-specific and time-variant. For example, the reputation of migrants from particular countries or the presence of people with the same nationality could accumulate over time and be specific to some countries. There is some evidence for what is called the 'friends and relative' argument, i.e. the fact that migrants are attracted to the locations where they have relations (see [8]). If the presence of migrants from the same nationality would affect GDP per capita, our estimates may be biased. Time-variant unobserved effects could also result from 'selective' migration policies, both in terms of skills and countries of origin, introduced by some OECD countries. Such factors could impact GDP per capita and potentially affect migration through channels other than those captured in the model. In addition, a causal interpretation could be problematic given the potential simultaneity problems that threaten the estimation of some variables. Our theoretical framework clearly points to a potential simultaneity: because migrants move with their demand for goods, affecting production in the migrant-receiving countries, they alter wages in both the country of origin and the destination country.[16]

To be more precise, our theoretical model suggests that rainfall and temperature anomalies affect the incentives to migrate through an amenity as well as an economic geography channel. While the amenity channel does not contain any

[16] Among others, Card [15], Friedberg and Hunt [34], Hunt [46] and Ottaviano and Peri [76] cannot find empirical evidence supporting this causal link. With the exception of Maystadt and Verwimp [58] who study the issue in the particular context of refugee hosting, no similar assessment has been undertaken in the African context.

sources of obvious estimation bias, the economic geography channel may contain possible endogeneities. The two main variables that comprise the economic geography channel are according to our theoretical model, wages and urbanization. Given the results of our theoretical model as well as those in Barrios et al. [4] we are well-aware that the size of the urban population is likely to be endogenous to wages, weather anomalies and several control variables. An increase in urbanization should theoretically increase the incentives to further migrate as migrants move with their income and strengthen agglomeration forces. This is what is usually referred to as the home market effect [52].

One approach to dealing with this simultaneity issue is by resorting to instrumental variables in a fixed effect framework that copes with unobserved time-constant and time-region heterogeneity. The challenge is to find a valid instrumental variable that will not affect the net migration rate through channels other than the potentially endogenous variable. In regression (1), we instrument GDP per capita with the absolute growth in the money supply. The relevance of this candidate rests on the importance of monetary variables in determining GDP variation.

Indeed, one of the most familiar rules in monetary policy is the Taylor rule, which links monetary policy with inflation and the output gap. Under this rule, which is followed by the Federal Reserve in the US, deviations from potential output should induce monetary policy actions, thus making money supply, at least for the US, endogenous to GDP. However, sub-Saharan African countries, like the Euro area countries, do not follow the Taylor rule; they focus only on fighting inflation. The exogeneity of the money supply and its correlation to GDP in sub-Saharan Africa is confirmed in Kasekende and Brownbridge [49],[17] who write that "[t]he implementation of monetary targeting frameworks in sub-Saharan Africa has, in practice, paid little attention to the stabilization of output." As a result, monetary policy in sub-Saharan Africa can be viewed as chiefly monetarist in nature. Hence, by changing the money supply, policy makers are able to induce changes in interest rates which affect the incentives for investments, and thereby production and wages. Indeed, contractions in the money supply have been shown to be the source of such strong contractions in production as those seen during the Great Depression [35], or as such large expansions as those seen the Great Moderation [12,6,17]. The channels through which monetary policy may affect production are now well-studied, and include direct channels like the interest rate, or indirect ones, like credit (see [16,36,62]). Hence, especially in countries with inflation targets like the sub-Saharan African countries, the causality clearly goes from monetary policy to GDP.

### 3.3. Results

We present the main results of this article in Table 4. As predicted by the theoretical model we find robust and statistically significant evidence for both the amenity channel and the economic geography channel. With respect to the amenity channel, we find that weather anomalies in agriculturally dependent countries induce out-migration. This finding supports the existence of environmental non-economic (non-market) pure externalities that exacerbate the incentives to move to another country. Similar evidence has been obtained by Rappaport and Sachs [79] and Rappaport [78] for the case of the US, and by Cheshire and Magrini [18] for Europe. These articles suggest that weather-related migration, in richer regions like the US or Europe, may be due to a larger relative valuation of the environment from rising per capita income. For sub-Saharan Africa, it seems unlikely that the significance of the amenity channel is due to the fact that people simply want to live in places with nicer weather *per se*. Instead, we would more strongly emphasize the view that the amenity channel most likely captures health-related or risk-reducing migration. Health-related migration would mainly be due to weather anomalies spreading diseases like malaria, dengue or meningitis [93]. Indeed, sub-Saharan Africa has more deaths from malaria or similar diseases than any other region in the world. Risk-reducing migration is likely due to the fact that a period of weather anomaly may be associated with higher future risks[18] and, consequently, migration might occur as a preventive step. Similar reasons have been advanced by Gutmann and Field [38] who examine return rates of previous inhabitants in the aftermath of hurricanes Katrina and Andrew.

With respect to the economic geography channel, we find the following. First, weather anomalies clearly impact wages (proxied by relative GDP per capita). This result confirms and complements previous works by Barrios et al. [5]. Furthermore, sub-Saharan African countries that have a large agricultural sector are particularly vulnerable. In regressions (1), (3) and (7), temperature anomalies have a negative impact on the GDP per capita ratio, in line with the findings in Dell et al. [23].[19] The interaction term of rainfall anomalies and the dummy for above-median agricultural added value (*AGRI*) have the expected positive sign. Given the significant and positive coefficient of the GDP per capita ratio in the second stage of the estimation procedure (see (2), (5), (6) and (9)), weather anomalies increase the incentives to migrate out of one's country of origin, particularly in countries that are highly dependent on the agricultural sector.

In line with Barrios et al. [4], weather anomalies strengthen the urbanization process in agriculturally dependent countries.[20] Given the role of agglomeration economies, such an increase in urbanization constitutes an attraction force for

[17] The authors are Deputy Governor and Economic Advisor to the Governor at the central bank of Uganda.

[18] There is evidence that climatic variables help explain malaria transmission [51].

[19] This result is useful in that it supports the assumption that temperature affects GDP which is the foundation for the whole integrated assessment literature, see e.g. Nordhaus [73].

[20] Further analyzes (available from the authors) show that our results on rainfall differ from those in Barrios et al. [4] because we have a different sample (migration data causes a reduction in the sample size). Although non-significant, our coefficients have a similar effect on urbanization, in terms of magnitude, as Barrios et al. [4]. They find that a 1% decrease in rainfall (i.e. −10 mm per year and per country) yields a 0.45% increase in urbanization. Our

**Table 4**
Two-stage regressions.

| Regression | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|---|
| Models | FE2SLS | FE2SLS | FE2SLS | FE2SLS | FE2SLS | FE2SLS LIML | FE2SLS | FE2SLS | FE2SLS |
| SE | Robust | Robust | Robust | Robust | Robust | Robust | Robust | Robust | Robust |
| Stage | 1st | 2nd | 1st | 1st | 2nd | 2nd | 1st | 1st | 2nd |
| Dependent variable | $\log(y/y^F)$ | MIGR | $\log(y/y^F)$ | log(URB) | MIGR | MIGR | $\log(y/y^F)$ | log(URB) | MIGR |
| RAIN | −0.0222 | 1.277 | −0.023 | −0.00332 | 0.843 | 0.843 | −0.0231 | −0.0034 | 0.845 |
| | [0.0140] | [0.978] | [0.0140] | [0.00832] | [0.832] | [0.832] | [0.0139] | [0.00830] | [0.833] |
| TEMP | −0.0457*** | 2.922** | −0.0432*** | −0.0204** | 2.841** | 2.842** | −0.0432*** | −0.0203** | 2.849** |
| | [0.0153] | [1.366] | [0.0153] | [0.00876] | [1.239] | [1.240] | [0.0153] | [0.00875] | [1.252] |
| RAIN∗AGRI | 0.0484*** | −2.608** | 0.0494*** | 0.00162 | −1.258 | −1.258 | 0.0495*** | 0.0017 | −1.26 |
| | [0.0187] | [1.314] | [0.0187] | [0.00997] | [0.936] | [0.936] | [0.0187] | [0.00995] | [0.937] |
| TEMP∗AGRI | 0.00702 | −1.382 | 0.00811 | 0.0455*** | −4.253** | −4.254** | 0.00807 | 0.0454*** | -4.268** |
| | [0.0217] | [1.297] | [0.0218] | [0.00980] | [1.693] | [1.694] | [0.0217] | [0.00979] | [1.715] |
| $WAR_{t-1}$ | −0.075 | 6.024 | −0.0738 | 0.0104 | 2.997 | 2.997 | −0.0738 | 0.0104 | 2.996 |
| | [0.0877] | [7.611] | [0.0877] | [0.0259] | [5.709] | [5.710] | [0.0876] | [0.0259] | [5.715] |
| $WAR^F_{t-1}$ | −0.183 | 7.869 | −0.182 | 0.02 [0.0850] | 0.86 [7.194] | 0.861 | −0.182 | 0.02 [0.0849] | 0.861 |
| | [0.150] | [9.281] | [0.150] | | | [7.195] | [0.150] | | [7.210] |
| $\log(y/y^F)$ | | 52.30** | | | 21.58*** | 21.59*** | | | 21.62*** |
| | | [20.57] | | | [7.216] | [7.219] | | | [7.286] |
| log(URB) | | | | | 67.51*** | 67.53*** | | | 67.83*** |
| | | | | | [24.14] | [24.15] | | | [24.55] |
| *Instruments* | | | | | | | | | |
| ΔMoney | 0.131** | | 0.131** | 0.0596 | | | 0.130** | 0.0591 | |
| | [0.0556] | | [0.0557] | [0.0350] | | | [0.0556] | [0.0349] | |
| New state UK | | | −0.641*** | 0.230*** | | | −0.671*** | 0.194*** | |
| | | | [0.0892] | [0.0484] | | | [0.0725] | [0.0323] | |
| New state | | | −0.0297 | −0.0362 | | | | | |
| | | | [0.0504] | [0.0338] | | | | | |
| HW-Dum | Incl. | Incl. | Incl. | Incl. | Incl. | Incl. | Incl. | Incl. | Incl. |
| Region-Dum | Incl. | Incl. | Incl. | Incl. | Incl. | Incl. | Incl. | Incl. | Incl. |
| Time-Dum | Incl. | Incl. | Incl. | Incl. | Incl. | Incl. | Incl. | Incl. | Incl. |
| Region-Time | Incl. | Incl. | Incl. | Incl. | Incl. | Incl. | Incl. | Incl. | Incl. |
| Observations | 750 | 750 | 750 | 750 | 750 | 750 | 750 | 750 | 750 |
| Number of countries | 39 | 39 | 39 | 39 | 39 | 39 | 39 | 39 | 39 |
| *F*-test | 61.85*** | 23.23*** | 88.87*** | 65.79*** | 22.17*** | 22.17*** | 93.85*** | 66.36*** | 19.33*** |
| *F*-test on excl. IV | 5.51** | | 30.84*** | 12.99*** | | | 46.24*** | 19.43*** | |
| Underid test | | 6.796*** | | | 7.595*** | 7.595*** | | | 7.124*** |
| *P*-value Hansen | | | | | 0.871 | 0.871 | | | |
| Endo stat | | 12.98*** | | | 14.53*** | 14.53*** | | | 13.26*** |
| Root MSE | .2288 | 13.04 | .2283 | .09746 | 10.82 | 10.82 | .2281 | .09738 | 10.84 |

**significant at 5%; *** significant at 1% (significance at 10% not highlighted). Robust standard errors are in square brackets. $y$ stands for domestic GDP per capita, $y^F$ stands for foreign GDP per capita. "HW-Dum" stands for the four dummies of Hatton and Williamson [41] for Ghana and Nigeria for the years 1983 and 1985, "Region-Dum" includes region dummies, "Time-Dum" time dummies and "Region-Time" time-region dummies. $t-1$ indicates a one period lagged variable. R-squared is not shown, because, in the case of 2SLS/IV, it is not an appropriate measure of the goodness of fit and has no statistical meaning (see www.stata.com).

international migrants. This is consistent with the mechanism described in our theoretical framework, where decreased rural wages lead to a larger urban concentration, while in turn stronger agglomeration forces provide incentives for in-migration. This result also finds support both with empirical New Economic Geography studies on the role of

(*footnote continued*)
(non-significant) rainfall coefficients indicate that a 1% decrease in rainfall induces a 0.98% (unweighted country average) and a 0.81% (population-weighted average) increase in urbanization. We note that even though temperature anomalies dominate in our sample, results on other samples e.g. Henry et al. [44], Barrios et al. [4] or regions ([66], for Mexico) emphasize the role of rainfall, while yet others emphasize the importance of temperature alone [25,14]. Thus, though different samples find robust results for an impact from weather anomalies, they differ as to whether rainfall or temperature is the main driver of those results. Since both drive evapotranspiration, the differences in results may arise from the possibility that for some countries, evapotranspiration is more strongly driven by temperature while in others rainfall might be more important simply due to geographic conditions or the local flora and fauna.

urbanization in attracting migrants [42] and more descriptive evidence on the importance of international migrants in African cities [7]. Given its positive and significant coefficient in the second-stage of the regressions, urbanization softens the impact of weather anomalies on international migration. Section 3.5 discusses the channels that dominate for international migration and provides estimates of the effect of weather anomalies on international migration.[21]

These results hinge crucially on the use of our three regression instrumental variables framework. As we argue above, only a unified framework may be able to simultaneously account for the channels that we identify within our theoretical framework. Thus, for consistency we describe our use of the instruments in more detail now. Our first-stage regression confirms that a decline in the growth of money is statistically associated with a fall in GDP per capita. A decrease by a standard deviation in money growth should reduce relative GDP per capita by about 11%. In regressions (3)–(5), we show results under overidentifying restrictions by introducing two additional instruments. We use a dummy to indicate whether a country experienced the two first years of independence, as well as the interaction of this variable with a dummy that takes the value of one if that country has been colonized by the UK. According to Miller and Singh's [61] catch-up hypothesis and consistent with the results of Barrios et al. [4], restrictions on internal movements during colonial times were followed by a strong urbanization after independence.[22] This has been observed particularly in former British colonies where the administration favored the establishment of new colonial urban centers [29]. Although Fig. 2 does not appear to depict a different trajectory in net migration in the years when most African countries became independent, we cannot exclude *a priori* the possibility that state independence has affected cross-border migration by another channel than rural–urban migration. However, using three instruments with two endogenous variables allows us to test the exogenous nature of these instruments (overidentification test). Beyond the reasonable nature of the overidentifying restrictions, statistical tests support our confidence in the validity of these instrumental variables. Provided at least one instrument is valid, the Hansen overidentification test fails to reject the null hypothesis of zero correlation between these instrumental variables and the error terms.

*F*-tests on excluded instruments equal 30.84 in first-stage regression (3) and 12.99 in first-stage regression (4). As suggested by Angrist and Pischke [3], we also test the robustness of the results under overidentifying restrictions to the Limited Information Maximum Likelihood (LIML) estimator. Regression (6) indicates that our results are unaltered with the LIML estimator; we can therefore reject the null hypothesis of weak instruments. In regressions (7), (8) and (9), we also follow Angrist and Pischke [3] in checking the robustness of our results to a just-identified estimation. Just-identified 2SLS is indeed approximately unbiased while the LIML estimator is approximately median-unbiased for overidentified models. When just-identified estimation is implemented, results do not change whether the dummy for the first two years of independence is introduced as an exogenous explanatory variable or not.[23]

### 3.4. Robustness

Robustness checks are not shown in the paper but are presented in Section 4 of Supplementary Material. These robustness checks relate to the use of alternative dependent variables, alternative definition of the main explanatory variables of interest and the addition or omission of control variables. Regarding the dependent variable, our results are robust to the definition used by Hatton and Williamson [41], i.e. without subtracting the net refugee flow from the migration rate but introducing it as an explanatory variable (see Table 5 in Supplementary Material). Since this dependent variable incorporates the movement of refugees, the net refugee flow (NetREF) exhibits a positive coefficient that is close to one. Although it unduly increases the risk of endogeneity, this inclusion does not alter our results.[24] Furthermore, we test the robustness of our findings to an alternative definition of our variables of interest (see Table 6 in Supplementary

[21] Our preferred specification (3)–(5) yields average partial effects (APEs) of rainfall and temperature in agriculturally dependent countries (Agri = 1) and in countries with below median agricultural GDP share (Agri = 0) taking on the following values: $APE_{RAIN,Agri=1} = 1.07$, $APE_{RAIN,Agri=0} = 0$, $APE_{TEMP,Agri=1} = -0.65$ and $APE_{TEMP,Agri=0} = 0.53$. These values account for the amenity and economic geography channel of weather on migration.

[22] Hance [39, p. 223] finds that restrictions on movements to the cities under colonial regimes greatly explain the low urban levels of less than 10% in the three main Eastern African countries (Ethiopia, Somalia and Kenya). According to Njoh [72], colonial authorities worked fervently to discourage Africans from living in urban areas. Governments in colonial Africa, and South Africa during the apartheid era, crafted legislation to prevent the rural-to-urban migration of native Africans. The covert goals of this policy were to preserve the 'white' character of the cities and keep the black population in the rural areas. As reported by Roberts [82] "colonial relationships between core countries and their dependencies set the stage for differences in urbanization among less-developed countries. In the colonial situation, provincial cities often served mainly as administrative and control centers to ensure the channeling for export of minerals, precious metals or the products of plantations and large estates; but wealth and elites tended to concentrate in the major city. When countries became independent and began to industrialize, it was these major cities that attracted both population and investment. They represented the largest and most available markets for industrialists producing for the domestic market. They also were likely to have the best infrastructure to support both industry and commerce in terms of communications and utilities."

[23] Beyond the question of internal validity, the use of instrumental variables restricts the external validity of our analysis. In other words, the economic geography channels between weather anomalies and migration are not only identified for a particular sample (sub-Saharan Africa) but also for a particular sub-population, i.e. those countries with 'monetarist' monetary policy for the income channel and those countries with a particular colonial history for the urban channel.

[24] Moreover, Hatton and Williamson [41] point out that demographic pressure is an important determinant of international migration. Our main results remain valid when introducing such a demographic variable in our specification with the lagged value of population density, which is significant and affects net migration negatively. However, potential endogeneity issues induced by the introduction of population density require us to be cautious with this specification. Furthermore, entry into the Asia-Caribbean-Pacific (ACP) agreements could also constitute another determinant of international migration. Completing the data supplied by Head et al. [43] on entry into the ACP with data for Botswana and Namibia, we find that addition of entry into

Material). Our results are unaltered when rainfall and temperature are expressed in terms of levels (with or without logarithmic transformation) rather than in terms of anomalies. Moreover, the inclusion of spatially and time lagged values for weather variables, which do not feature significant explanatory power, does not change our main results. Using alternative definitions for GDP per capita does not change our findings. In fact, our main results are confirmed when replacing GDP per capita by GDP per worker, using the Chain transformation instead of the Laspeyres index in the real terms transformation (see Table 7 in Supplementary Material), and when exploiting alternative weights in the spatial decay function to compute the foreign wage (see Table 8 in Supplementary Material). These alternative weights include proxies other than the distance for migration costs, including colonial link, contiguity, a common colonial ruler and linguistic proximity. Moreover, we also test the robustness of our results to the omission of some control variables (see Table 9 in Supplementary Material). Following Miguel et al. [60], Burke et al. [14] and Hsiang et al. [45], we cannot exclude that possibility that weather affects conflict; therefore, inclusion of the conflict variable may wipe out some of the explanatory power of our weather variables. Therefore, the inclusion of the conflict-related variables may undermine our estimations of weather-induced migration. Although introducing a potential omitted variable bias, omitting the conflict-related variable does not alter the main results of this paper. Finally, we test the robustness of our results to an alternative dependent variable based on bilateral migration flows between our 39 SSA countries and 14 OECD destination countries (see Table 10 in Supplementary Material based on data from Ortega and Peri [74,75]). Results obtained from two-stage estimations like those in our baseline confirm the main findings presented in Table 4. As with Mayda [56], we find that a higher GDP per capita at origin or lower GDP per capita at destination reduces out-migration. Moreover, these robustness results indicate that a decrease in rainfall anomalies increases the economic incentive to migrate out of countries highly dependent on the agricultural sector while an increase in temperature anomalies increases that economic incentive. Our main findings hold, therefore, also for migration outside Africa.

It is likely that our proxy for the domestic wage could be subject to measurement errors and thus potentially bias our results.[25] Nevertheless, we believe that this should not significantly influence our results for the following reasons. First, these measurement errors are partly dealt with through the use of the instrumental variables. Second, by restricting the sample to sub-Saharan African countries, we are more likely to have relatively similar GDP and institutional structures, which is an important determinant of sound comparisons over time [22]. Third, as indicated above, we find that our results are robust to alternative GDP per capita measurements.

### 3.5. Projections

Overall, our results suggest that weather anomalies increase the incentives to migrate to another country. In this section we provide a tentative estimation of weather-induced migration flows in sub-Saharan Africa. We first estimate the historical migration flows induced by weather anomalies over the period 1960–2000. Subsequently, we provide an end of century projection for the change in migration flows based on IPCC forecasts for potential weather scenarios and based on population projections from the UN. Our computations are based on the significant coefficients of the weather variables as well as on the coefficients of the GDP per capita ratio and the urbanization variables in regressions (3)–(5) of Table 4. More details can be found in Supplementary Material.

#### 3.5.1. Historical estimates

We compute the contribution of weather changes to past migration in sub-Saharan Africa over the period 1960–2000. Our calculations are based on the significant coefficients of our preferred regressions (3)–(5) in Table 4 and on observed weather data in the 39 countries of our sample. Our findings yield that, during the second half of the 20th century, on average 0.3 per thousand individuals in sub-Saharan Africa (i.e. 0.03% of the population) living in the countries most exposed to weather anomalies (i.e. highly dependent upon the agricultural sector), were displaced each year due to changes in temperature and precipitation (see first column of Table 6). Table 6 also indicates the share of this weather-induced migration that is due to rainfall and temperature as well as the fraction that is due to the amenity effect of weather and to the economic geography effects (GDP per capita ratio and urbanization). Rainfall changes drove changes in net migration more strongly than temperature did over the period 1960–2000 (the contribution of temperature and rainfall anomalies to the over effect was 47% and 53%, respectively). Weather anomalies affected international migration mainly through the economic geography channel. Our estimate of 0.3 per thousand individuals corresponds *in net figures* to the annual average displacement of 128,000 individuals due to weather anomalies over the period 1960–2000, which

(*footnote continued*)
ACP as a control variable does not alter the main results and does not produce significant coefficients (with the exception of the effect on the GDP ratio). These results are shown in Supplementary Material.

[25] One would expect these errors to be largely dependent on the institutional environment of the countries concerned. In this case, these errors would not cause any bias if they were constant over time or time-specific, as we use country- and time-specific fixed effects. Nevertheless, since some countries may have experienced institutional changes that introduced variability into the measurement error then this could potentially leave some room for bias. For example, poor countries may be more likely to have a less developed statistical capacity and migration data may be more likely to be based on the residual approach, or more inclusive of illegal and undocumented migrants. Consequently, a change in economic development and statistical capacity may be associated with a change in demographic accounting methodology, for example from a residual to an observational approach. In that case, the estimated coefficient of the GDP ratio is likely to feature a downward bias.

**Table 5**
IPCC projected changes in rainfall and temperature.
*Source:* IPCC Fourth Assessment Report, Scenario A1B [19].

| Region | Projected change in rainfall | | | Projected change in temperature | | |
|---|---|---|---|---|---|---|
| | Best (%) | Median (%) | Worst (%) | Best | Median | Worst |
| Saharan | 57 | −6 | −44 | 2.6 | 3.6 | 5.4 |
| West | 13 | 2 | −9 | 1.8 | 3.3 | 4.7 |
| East | 25 | 7 | −3 | 1.8 | 3.2 | 4.3 |
| South | 6 | −4 | −12 | 1.9 | 3.4 | 4.8 |

Columns "worst", "median" and "best" correspond to the less optimistic, medium and most optimistic weather changes of the IPCC's scenario A1B, i.e. 75%, 50%, and 25% quartile values for projected changes in precipitation (%) and to the 25%, 50%, and 75% quartile values for projected changes in temperature (°C) between the period 1980–1999 and the period 2080–2099.

represents only about 3% of the 4 million annual internal (rural–urban) migrants caused by weather anomalies. Therefore, in total over the period 1960–2000, 5 million people have been displaced due to weather anomalies. Such a figure may seem rather low, but given the 'net' nature of our dependent variable, it represents a lower bound estimate.[26]

### 3.5.2. End of century projections

To give a rough estimate of the possible consequences of future weather anomalies on migration flows in sub-Saharan Africa, we make use of the climate projections described in the Fourth Assessment Report (AR4) of the United Nations Intergovernmental Panel on Climate Change (IPCC). The IPCC projections are drawn from various climate models and scenarios and provide estimates on the future *change* in regional temperature and precipitation between the periods 1980–1999 and 2080–2099. Our migration projections are based on weather anomalies given by scenario A1B, which is described in detail in Chapter 11 of the IPCC report [19, p. 854] the report's forecasted weather changes are reproduced in Table 5. This scenario seems reasonable as it assumes greater economic integration in the future, which is in line with recent economic growth trends of emerging countries (China, India and even sub-Saharan Africa). Furthermore, assumptions regarding future green house gas emissions and the world population are moderate (see further details in Supplementary Material).

Projections indicate that an additional 1.21–5.32 per thousand individuals in sub-Saharan Africa will be induced to migrate annually due to varying weather conditions towards the end of the 21st century (see columns 2–4 of Table 6). The UN Population Division provides projections of population changes over the 21st century according to low-, medium- and high-fertility scenarios [90]. Applying our projected net migration rates to these estimated population changes yields, in net terms, the additional annual environmental migrants for the period 2080–2099 compared to the period 1980–1999. The additional annual net migrants are comprised between 2.9 million (in the low-fertility/best-weather-change scenario) and 25 million (in the high-fertility/worst-weather-change scenario). We can now look at disaggregated effects. In the best and median weather-change cases, precipitations are projected to rise (see Table 5), and thus temperature is alone responsible for any increase in net migration in those cases (see columns 2 and 3 of Table 6). Moreover, the buffering role of urban centers is strengthened compared to the period 1980–1999 while the amenity channel plays a more significant role than in the past, *Ceteris paribus*.

Our country-specific results are presented in a map (Fig. 3).[27] While there has been a long tradition of migration to the coastal agglomerations in Africa [1], a significant proportion of the coastal population may flee toward inland Africa due to weather changes by 2099. Countries that would be affected by coastal flight, by region, are as follows. In Western Africa the most affected countries include Benin, Ghana, Guinea, Guinea-Bissau, Nigeria and Sierra Leone; in Eastern Africa, Kenya, Madagascar, Mozambique, Tanzania and Uganda; in Southern Africa, Angola and Botswana; and in Central Africa, Congo and Gabon.

Concerning the end of century projections we have to add that, given the non-negligible number of environmental migrants we estimate, some of our assumptions may not continue to hold. In particular, there might be a strong divergence between the desire to migrate versus the capacity to do so.[28] For example, if there are large and persistent migration flows from one country into another, then the potential receiving country could restrict migration, as Europe did for migrants

[26] We find that, in net terms, 0.851 people out of 1000 individuals living in sub-Saharan Africa (SSA) left their country every year over the period 1960–2000. This value is obtained by computing the number of net migrants from countries with a *negative* average net migration rates over the period 1960–2000 divided by total SSA population. Similarly, by focusing on countries with positive average net migration rates, we find that 0.637/1000 migrated to another of the 39 SSA countries of our sample. The difference between these two values indicates that 0.241/1000 migrants moved to countries outside of our 39. Considering only the effect of weather changes, we find that 0.305/1000 left one of the 39 SSA countries, 0.159/1000 found home in another of these 39 countries and 0.146/1000 in another country of the world. This means also that 35.83% (305/851) of people leaving their country did so because of weather changes.

[27] For illustrative purposes, the map displays values for Cape Verde, Guinea-Bissau, Somalia and South Africa. These countries were dropped from our initial sample due to too few observations on various variables. To include them in the map, we applied our coefficients to available data on migration, population and weather for these countries.

[28] We are grateful to one referee for suggesting this line of thought.

**Table 6**
Weather-induced migration for the sub-Saharan Africa region.

| | **1960–2000** | **Projections for the end of the 21st century** (*Additional migration induced by weather changes between* 1980–1999 *and* 2080–2099) | | |
|---|---|---|---|---|
| | | Best | Median | Worst |
| *A. Main results: Weather-induced net migration rates* | | | | |
| Annual net (international) migration rate[a] | **−0.30** | | | |
| Additional annual net migration rate[a,b] | | **−1.21** | **−3.40** | **−5.32** |
| *B. Using population data: absolute numbers of weather-induced migrants* | | | | |
| Annual number of net international migrants[c] | **−128’414** | | | |
| Annual number of *internal* migrants[c,d] | 4’206’729 | | | |
| Total number of net international migrants in 40 years | −5’136’569 | | | |
| Total number of *internal* migrants in 40 years[d] | 168’269’153 | | | |
| Additional annual net migrants (low-fertility)[b,e] | | −2’910’008 | −8’493’369 | −13’332’808 |
| Additional annual net migrants (medium-fertility)[b,e] | | −4’053’671 | **−11’784’960** | −18’477’402 |
| Additional annual net migrants (high-fertility)[b,e] | | −5’528’551 | −16’014’948 | −25’080’975 |
| *C. Disaggregated results: contribution in %* | | | | |
| *Contribution of rainfall and temperature anomalies to net international migration* | | | | |
| Temperature | 47% | 162% | 103% | 92% |
| Rainfall | 53% | −62% | −3% | 8% |
| *Contribution of amenity and economic geography channel to net international migration* | | | | |
| Amenity channel | 101% | 352% | 224% | 200% |
| GDP per capita (economic geography channel) | 120% | 170% | 145% | 140% |
| Urban population (economic geography channel) | −121% | −422% | −269% | −241% |

The table displays net (international) migration rates and the net number of (international) migrants displaced out of SSA countries due to weather changes over the period 1960–2000. It also presents projections for the end of the 21st century. Negative numbers for net international migration mean that there were more emigrants than immigrants.

[a] Net migration rates are expressed in 1000 of population.
[b] These numbers are absolute changes with respect to the 1960–2000 period.
[c] Calculated using 1960–2000 population averages.
[d] Refers to rural–urban migration, i.e. increases in urbanization.
[e] *Additional annual net migrants* refers to the projected annual increase in weather-induced international migration compared to the annual average over the period 1960–2000. In the (i) low-fertility, (ii) medium-fertility and (iii) high-fertility cases, the projected increase in the number of migrants is obtained by multiplying the projected increase in net migration rates of the second row with the population average over the period 2080–2099 of the corresponding UN projections scenario (i.e. the (i) low-fertility population scenario, (ii) medium-fertility population scenario and (iii) high-fertility population scenario).

from Africa and as the US did for migrants from Mexico. Additionally, problems of infrastructure and property rights may evolve. Then, massive population movements could speed up the transmission of epidemic diseases such as malaria [64] in areas where the population has not yet developed protective genetic modifications [10]. Finally, the expected move towards inland Africa could become a major geopolitical concern since population density, ethnic differences and social disparities have been recognized as factors enhancing conflicts; these factors have been found relevant for the conflicts in North-Kivu in Congo, Burundi [13], Rwanda [2] or also Darfur [28]. Naturally, such consequences remain to be verified both theoretically and empirically in order to formulate stronger statements about the relationship between migration flows and the onset of conflicts.

## 4. Conclusion

The problems associated with weather anomalies certainly rank as one of the important issues of our times. However, little academic evidence has been provided regarding one of its most often discussed consequences, namely human migration. In this article we propose a theoretical framework featuring rural–urban–international migration as a consequence of weather anomalies. Our theoretical model predicts that weather anomalies should work their way into international migration through two channels. First, the theoretical model predicts that weather anomalies will lead to lower rural wages, particularly if the effect of weather anomalies on agricultural production is sufficiently strong. Second, the model predicts that the lower rural wages will then induce nationally mobile workers to move from the country-side into the cities in search of work. Weather anomalies are therefore a key determinant of urbanization. Finally, by decreasing the urban wage via the influx of available workers, this rural–urban flow in turn magnifies the incentives of the internationally mobile worker to move to another country. However, due to agglomeration economies, an increase in urbanization tends to mitigate the impact of weather anomalies on international migration.

Using the results of our theoretical work as guidance for an empirical analysis of the impact of weather anomalies on international migration in sub-Saharan Africa, we find that weather anomalies have a significant and robust impact on average wages. This result supports work by Barrios et al. [5] and Dell et al. [23], who show that weather anomalies have an important impact on GDP per capita. We find that wages are robust and significant determinants of international

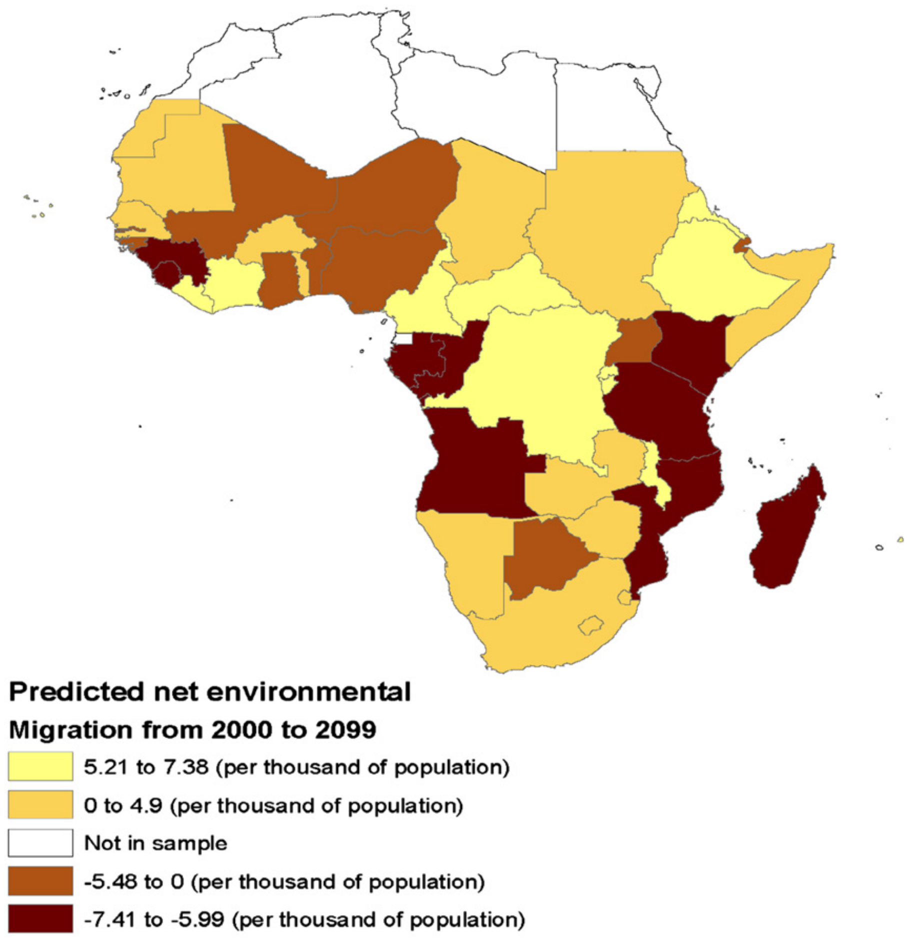


**Fig. 3.** Projected net environmental migrants per thousand of population, 2000–2099.

migration and show that weather anomalies directly affect international migration, reflecting possible pure externality effects of weather anomalies. We dub this the amenity channel. Next, we observe that weather anomalies increase incentives to move to the cities. This channel of transmission is consistent with Barrios et al. [4] who show that weather anomalies in Africa displace people internally. We also find that urban centers represent an attraction force; thus urbanization softens the impact of weather anomalies on international migration. We label these effects, via wages and urbanization, the economic geography channel.

Overall we conclude that a minimum of about 5 million people have migrated between 1960 and 2000 due to anomalies in local weather in sub-Saharan Africa. This represents 0.3 per thousand individuals or 128,000 people every year. We then project the impact of weather anomalies on the future rates of migration in sub-Saharan Africa. Considering the medium-fertility population forecast of the United Nations, our main results are that in sub-Saharan Africa towards the end of the 21st century every year an additional 11.8 million inhabitants may move as a consequence of weather anomalies.

These results impose serious and challenging questions for policy makers. After all, African countries account for only approximately 5% of world greenhouse gas emissions. If one believes that an increase in weather anomalies is human-induced, then these variations are nearly exclusively driven by the developed world. This externality thus imposed on the sub-Saharan countries requires international attention based on equity and fairness criteria. In this respect, the recent advances presented in the Cancun Agreement provide a good starting point. However, one of the important components of the Cancun Agreement, namely Nationally Appropriate Mitigation Actions, will not be a useful policy tool for Africa due to the relatively low total emissions. Future policies should therefore focus more closely on adaptation policies. As argued by Collier et al. [21], efforts aiming at making crops less sensitive to weather anomalies are the most obvious policy recommendation. Easing the market reallocation from agriculture to manufacturing sectors and emphasizing the absorption role of urban areas will also reduce the social costs of weather anomalies. However, our paper also qualifies the market-oriented solution promoted by Collier et al. [21]. Specific policies easing the factor absorption capacity at a national level or providing compensation mechanisms at a supra-national level should help countries deal with the human capital depletion that threatens some of the most affected countries.

Our projections also warn us about possible consequences in terms of health and security that such population movements could have on their migrant-receiving nations. Provided one is concerned about the security consequences of environmental migration, strengthening the buffering role of urban centers may constitute a policy option. In that respect, reducing congestion costs and improving transport infrastructure may enhance the absorptive capacity of agglomeration centers.

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## Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jeem.2012.02.001.

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