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RESEARCH PAPER

The geography of climate migration

Michał Burzyński[1], Frédéric Docquier[1]* and Hendrik Scheewel[2]

[1]LISER, Luxembourg Institute of Socio-Economic Research, Esch-sur-Alzette, Luxembourg and [2]Université de Liège and IRES, UCLouvain, Liège, Belgium
*Corresponding author. E-mail: frederic.docquier@liser.lu

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Abstract
In this paper, we investigate the long-term effects of climate change on the mobility of working-age people. We use a world economy model that covers almost all the countries around the world, and distinguishes between rural and urban regions as well as between flooded and unflooded areas. The model is calibrated to match international and internal mobility data by education level for the last 30 years, and is then simulated under climate change variants. We endogenize the size, dyadic, and skill structure of climate migration. When considering moderate climate scenarios, we predict mobility responses in the range of 70–108 million workers over the course of the twenty-first century. Most of these movements are local or inter-regional. South–South international migration responses are smaller, while the South–North migration response is of the "brain drain" type and induces a permanent increase in the number of foreigners in OECD countries in the range of 6–9% only. Changes in the sea level mainly translate into forced local movements. By contrast, inter-regional and international movements are sensitive to temperature-related changes in productivity. Lastly, we show that relaxing international migration restrictions may exacerbate the poverty effect of climate change at origin if policymakers are unable to select/screen individuals in extreme poverty.

Key words: Brain drain; climate change; migration; urbanization

JEL classification: E24; F22; J24; J61; 015; Q54

1. Introduction

Global warming and rising sea levels are two major components of long-term climate change that are highly likely to affect many economic outcomes in the coming decades [see Dell *et al.* (2014)]. However, the magnitude of these long-term economic consequences is uncertain, as the predicted effects of climate change have barely started to materialize. It is indisputable that sea levels and the global mean surface temperature of the world have increased since the beginning of the nineteenth century (by 0.9 °C and by 0.2 m, respectively), and that the process has accelerated since 1980. However, climatologists predict larger changes for the decades ahead. Leaving aside extreme scenarios, temperatures are expected to increase by 1–4° over the twenty-first century, and the sea levels are expected to rise by 0.5–2 m by 2050 [e.g., Rigaud *et al.* (2018)]. Hence, researchers are in uncharted territory and long-term extrapolation of existing empirical estimates is questionable.

In this context, we propose a structural approach to investigate the long-term effects of climate change on the size, skill composition, and dyadic structure of human mobility. Literature to date has mostly looked at the short-term impact of fast-onset variables (weather anomalies, storms, hurricanes, torrential rains, floods, landslides, etc.), as opposed to slow-onset variables (e.g., temperature trends, desertification, rising sea level, coastal erosion, etc.).[1] By contrast, we focus on long-term climate change, subsumed in temperature and sea level scenarios. Damage from long-term climate change is expected to vary across and within countries according to the proximity of seas and oceans, land topography, industry structure, and initial temperature levels. Empirical estimates consistently show that the impact of climate change on productivity will be greater in agriculture than in manufacturing [e.g., Dell *et al.* (2014); Desmet and Rossi-Hansberg (2015)]. In particular, climate change is expected to negatively affect crop production in low-latitude countries, while inducing much smaller or even positive effects in northern latitudes. Poor countries that have contributed the least to climate change will be the most adversely affected, and migratory pressures—both internal and international—will presumably be strongest in poor countries.

To provide a quantitative economic evaluation of the size and structure of climate migration, we use a micro-founded overlapping generations model of the world economy. The model distinguishes between 179 countries, each with two regions—agricultural and non-agricultural—and two areas per region—flooded and non-flooded. The regional dimension allows us to model sector-specific responses to climate change, including voluntary migration decisions (i.e., decisions driven by economic incentives), while the identification of flooded areas allows us to model forced displacements. Each area is initially populated by two types of natives (college graduates and the less educated) who exhibit heterogeneous migratory behaviors. Their mobility decisions determine the geographic distribution and skill structures of the labor force, productivity, and wage rates.

The essence of our approach is in line with Desmet and Rossi-Hansberg (2015) or Shayegh (2017), although we use a different level of spatial aggregation and climate change is exogenously subsumed in the simulation scenario rather than being a result of explicitly modeled mitigation decisions. We also differ in the way we formalize migration decisions. We assume a random utility structure, which allows us to account for the interplay between alternative forms of migration: international, inter-regional (i.e., rural-to-urban), and local (i.e., within a region). We thus explicitly model the choice of the destination country/region/area in a dyadic

[1]While climate change has consistently emerged as a potent driver of internal migration [Barrios *et al.* (2006); Dallmann & Millock (2017); Henderson *et al.* (2017); Kubik & Maurel (2016); Piguet *et al.* (2011)], there is no consensus regarding its effect on international migration. Some studies find important international migration outflows that are directly associated with weather shocks [Backhaus *et al.* (2015); Cai *et al.* (2016); Coniglio & Pesce (2015)] or indirectly induced by climate change driven pressures on living standards in urban areas [Beine & Parsons (2015); Marchiori *et al.* (2012, 2017)]. Others attempt to explain why migration responses to climate shocks have been small, non-existent, or even negative [Black *et al.* (2013); Black *et al.* (2011); Cattaneo et al. (2019)]. Recent reviews of the relevant literature can be found in Perch-Nielsen *et al.* (2008), Piguet *et al.* (2011), Berlemann and Steinhardt (2017), and Cattaneo et al. (2019).

structure, with both OECD (Organisation for Economic Co-operation and Development) destinations and developing countries. We parameterize our model so as to match socio-demographic and economic moments for the year 2010 or for the period 1980–2010. We use this calibrated model to simulate the trajectory of the world economy under alternative climate change scenarios and under constant migration laws and policies.[2]

We find that climate change reinforces divergence in total factor productivity (TFP) between rich and poor countries, and between urban and rural regions. It thus creates conditions that are conducive to increasing urbanization and international migration. Our baseline scenario corresponds to the mean emissions scenario (termed *RCP-4.5*) and its mean temperature variant, available from the CCKP (Climate Change Knowledge Portal) [Taylor *et al.* (2012)].[3] This scenario can be considered as moderate as it involves mean increases in temperature and sea level of 1.8 °C and 0.47 m, respectively [Stocker *et al.* (2014)]. For *RCP-4.5*, our model predicts 29.5, 20.9, and 19.1 million climate migrants in 2040, 2070, and 2100, respectively. This corresponds to a total of about 70 million individuals aged 25–64 years over the course of the twenty-first century (adding dependent children, this means a total of 130 million climate migrants approximately). More than half of these climate-related moves are local (forced displacements) or inter-regional (from rural to urban). Consistently, long-term climate change has a small effect on South–South (S–S) migration (i.e., migration between countries sharing similar climate patterns) and a limited impact on South–North (S–N) migration. This is particularly true for the first half of the twenty-first century. On average, under constant migration laws and policies, climate change induces a 4.6% permanent increase in the number of immigrants living in the OECD countries by 2040, and a 7.2% increase by 2100. Climate-driven pressures on S–N migration are small compared with those induced by the expected socio-demographic changes in developing countries. Importantly, S–N climate migrants are positively selected along the skill dimension, implying that international climate migration is of the brain drain type, and thus reinforces the inequality effects of climate change [Biavaschi *et al.* (2020)]. The greatest projected income losses are for the poorest workers trapped in the poorest regions (i.e., rural regions in low-latitude countries); climate change increases extreme poverty on the extensive and intensive margins. Given positive selection, relaxing international migration restrictions may exacerbate the brain drain and the poverty response to climate change if policymakers are unable to select/screen the extreme poor.

When doubling the predicted changes in temperature, the number of climate migrants reaches 108 million over the course of the twenty-first century (i.e., an additional 38 million compared with *RCP-4.5*). This includes 41.1 million people moving from developing to high-income countries, inducing a permanent increase by 9% in the total number of immigrants to OECD countries. This is relatively small given the huge impact of climate change on productivity. When doubling the

[2]The calibrated moving costs (reflecting all legal barriers as well as the private monetary and psychical costs of moving) are such that the model perfectly matches international mobility and urbanization data from the last 30 years. The backcasting exercises conducted in Dao *et al.* (2018) and Burzyński *et al.* (2020) demonstrate that such a model accurately fits the past migration trends and generates sensible projections.

[3]CCKP stands for the World Bank's Climate Change Knowledge Portal, which provides global data on future climate vulnerabilities and effects (https://climateknowledgeportal.worldbank.org/).

predicted rise in sea levels, local movements increase by 21 million compared with *RCP-4.5*, while additional inter-regional and international migration flows are small. Overall, our results suggest that forced displacements due to rising sea levels are mostly local (i.e., from flooded to non-flooded areas within the same region), while inter-regional and international mobility responses are limited and overwhelmingly governed by the TFP responses to temperature changes.

The rest of the paper is organized as follows. Section 2 describes the two-sector, two-skill-group model used to predict the behavioral and market responses to climate change (CLC). We summarize our parameterization strategy in section 3. Section 4 presents the results obtained under various climate scenarios. Section 5 concludes.

2. Model

To estimate the mobility responses to climate change, we set up an overlapping generations model of the world economy that endogenizes the dyadic and skill structures of migration. We model migration decisions as an outcome of a micro-founded, random utility maximization (RUM) model that jointly accounts for the main migration mechanisms through which climate change affects long-term migration. The RUM structure allows us to model the long-term mobility responses to climate change at various spatial scales, taking into account the interplay between alternative forms of migration: specifically local (i.e., very short distance), rural to urban (i.e., short distance), and international (i.e., long distance). Endogenous migration decisions are embedded in a general equilibrium framework with endogenous income distribution. Therefore, the effects of climate change on human mobility, global income inequality, and extreme poverty are jointly determined. Our framework assumes exogenous socio-demographic trends in line with the United Nations median scenario, and does not account for capital and trade. We discuss these assumptions in section 2.4. The model relies purely on a production technology and a migration technology.

More specifically, our model depicts a large set of countries and regions. Countries are denoted by$j = 1, \dots, J$, and comprise two regions (a region is equivalent to a production sector in our context) having heterogeneous productivity levels, with $r \in \{a, n\}$ denoting agriculture (a) and non-agriculture (n). The double index jr is used to identify a country-region location. Each region consists of two areas of time-varying size, with the subscript $b \in \{f, d\}$ denoting the flooded area (f) and the non-flooded/dry area (d). Floods are permanent and caused by rising sea levels; they materialize at the beginning of the period. There is no economic activity and no one can live in the flooded area. Hence, we distinguish between individuals who grew up in a region that becomes flooded and were forced to move in adulthood, and those who grew up in a non-flooded region and could choose between staying or leaving. This allows us to distinguish between forced displacements (driven by the sea level rise) and voluntary migration (driven by economic incentives).

Individuals live for two periods (childhood and adulthood). One period represents the active life of one generation (30 years); for simplicity, we ignore the retirement period. Adults are the only decision makers. For each location jr and each period, we distinguish between two types of adults, with $s \in \{h, l\}$ denoting college-educated workers (h) and the less educated (l). This allows us to account for the high degree of heterogeneity in migratory behavior between people of different places of origin and levels of education. We use $N^{jr}_{b,s,t}$ to denote the number of new adults of type s

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born in the area b of location jr at time $t-1$ (i.e., becoming adult at time$t$). The total native population in location jr is defined as $N_{s,t}^{jr} = N_{d,s,t}^{jr} + N_{f,s,t}^{jr}$. Adults maximize their utility by deciding where to live. That is, whether to stay in the region where they grew up (if the area where they were born does not become flooded), to move locally within the same region (if the area where they were born becomes flooded), to emigrate to the other region within the same country, or to emigrate abroad. This choice depends on the livability of the area of origin, on economic disparities across regions and countries, and on the cost of moving. It determines the number of residents in each (non-flooded) location, denoted by $L_{s,t}^{jr}$.

In this section, we describe our production and migration technologies (sections 2.1 and 2.2), and derive the profit and utility maximization conditions. We then define the world-economy intertemporal equilibrium in section 2.3. We discuss our simplifying assumptions in section 2.4.

2.1 Production technology

The production technology determines the wage rates in each location. Production is feasible only in the non-flooded area of each location jr. Output is proportional to labor in efficiency units, and for simplicity, we assume that firms in both sectors produce the same good. Each location is characterized by a constant elasticity of substitution production function with two types of workers [as in Burzyński *et al.* (2020); Gollin *et al.* (2014); Vollrath (2009)]. The output level in location jr at time t is given by:

$$Y_t^{jr} = A_t^{jr} \left(\frac{\eta_t^{jr}}{1+\eta_t^{jr}} L_{h,t}^{jr\,\frac{\sigma^r-1}{\sigma^r}} + \frac{1}{1+\eta_t^{jr}} L_{l,t}^{jr\,\frac{\sigma^r-1}{\sigma^r}} \right)^{\frac{\sigma^r}{\sigma^r-1}} \quad \forall t, r, \tag{1}$$

where A_t^{jr} denotes the productivity scale factor in location jr at time t (referred to as TFP henceforth), η_t^{jr} is a sector-specific variable governing the relative productivity of college-educated workers at time t (i.e., a skill bias in productivity), and σ^r is the sector-specific elasticity of substitution between the two types of workers. Remember the number of adult workers of type s employed in location jr at time t is denoted by $L_{s,t}^{jr}$.

The labor market is competitive. Wage rates are determined by the marginal productivity of labor:

$$\begin{cases} w_{h,t}^{jr} = A_t^{jr\,\frac{1}{\sigma^r-1}} \left(\frac{\eta_t^{jr}}{1+\eta_t^{jr}} L_{h,t}^{jr\,\frac{\sigma^r-1}{\sigma^r}} + \frac{1}{1+\eta_t^{jr}} L_{l,t}^{jr\,\frac{\sigma^r-1}{\sigma^r}} \right)^{\frac{1}{\sigma^r-1}} \frac{\eta_t^{jr}}{1+\eta_t^{jr}} L_{h,t}^{jr\,\frac{-1}{\sigma^r}} \\ w_{l,t}^{jr} = A_t^{jr\,\frac{1}{\sigma^r-1}} \left(\frac{\eta_t^{jr}}{1+\eta_t^{jr}} L_{h,t}^{jr\,\frac{\sigma^r-1}{\sigma^r}} + \frac{1}{1+\eta_t^{jr}} L_{l,t}^{jr\,\frac{\sigma^r-1}{\sigma^r}} \right)^{\frac{1}{\sigma^r-1}} \frac{1}{1+\eta_t^{jr}} L_{l,t}^{jr\,\frac{-1}{\sigma^r}} \end{cases} \quad \forall t, r.. \tag{2}$$

It follows that the wage ratio between high-skilled and low-skilled workers in location jr at time t is given by:

$$\varpi_t^{jr} \equiv \frac{w_{h,t}^{jr}}{w_{l,t}^{jr}} = \eta_t^{jr}(z_t^{jr})^{\frac{-1}{\sigma^r}} \quad \forall t, r, \tag{3}$$

where $z_t^{jr} \equiv L_{h,t}^{jr}/L_{l,t}^{jr}$ is the skill ratio in employment in location jr at time t.

In our setting, climate change affects production and income differentials through two channels. First, variations in temperature influence TFP in agricultural and in the non-agricultural sector. Second, climate change affects mobility decisions, which in turn impact on the skill ratio in the labor force. To account for these effects, damage functions and technological externalities are factored in. For TFP, we assume that the aggregate TFP level in each sector depends on the temperature level and the average level of workers' education. We thus have:

$$A_t^{jr} = \gamma^t \bar{A}^{jr} G(T_t^{jr}) F(z_t^{jr}) \quad \forall t, r, \tag{4}$$

where γ^t is a time trend in productivity that is common to all countries ($\gamma > 1$), $\bar{A}^{jr}$ is the exogenous component of TFP in location jr (reflecting specific local factors such as the proportion of arable land, soil fertility, land ruggedness, etc.), $G(T_t^{jr})$ links TFP to temperature (T_t^{jr}), while $F(z_t^{jr})$ is a simple Lucas-type aggregate externality [see Lucas (1988)] capturing the fact that college-educated workers facilitate innovation and/or the adoption of advanced technologies. We assume $F(z_t^{jr}) = (z_t^{jr})^{\epsilon_r}$ is a concave function of the skill ratio in employment, where $\epsilon_r \in (0, 1)$ is the sector-specific elasticity of TFP to the skill ratio in region/sector r of all countries. With regard to the effect of temperature, existing literature suggests that TFP levels in agriculture and non-agriculture can be represented by sector-specific, inverted-U-shaped functions of (T_t^{jr}), as discussed in section 3 [Desmet *et al.* (2018); Shayegh (2017)].

With regard to the skill bias, we assume directed technical change that affects different types of workers non-uniformly. As technology improves, the relative productivity of college-educated workers increases, particularly in the non-agricultural sector [Acemoglu (2002); Restuccia and Vandenbroucke (2013)]. The observed relative demand shift favors college-educated over non-college-educated labor. We thus have:

$$\eta_t^{jr} = \bar{\eta}^{jr}(z_t^{jr})^{\kappa_r} \quad \forall t, r, \tag{5}$$

where $\bar{\eta}_{jr}$ is an exogenous term and $\kappa_r \in (0, 1)$ is the sector-specific elasticity of the skill bias to the skill ratio in sector/region r of all countries.

2.2 Migration technology

To model migration decisions, our RUM model assumes that the utility of moving to a given location is the sum of deterministic and random components. The deterministic part has a logarithmic functional form and depends on the local wage rate at destination and the costs of moving. The random part captures heterogeneity in preferences or in moving costs. Hence, the utility of an adult of type s, born in the area b of a location of

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origin jr, moving to the (non-flooded) area of a location $j'r'$ is given by:

$$U_{b,s,t}^{jr,j'r'} = \ln w_{s,t}^{j'r'} + \ln\left(1 - x_{b,s,t}^{jr,j'r'}\right) + \xi_{b,s,t}^{jr,j'r'} \quad \forall s,\, t,\, jr,\, j'r' \tag{6}$$

where $\ln w_{s,t}^{j'r'} \in \mathbb{R}$ is the deterministic level of utility that can be reached in the location $j'r'$ at period t and $x_{b,s,t}^{jr,j'r'} \leq 1$ captures the effort required to migrate from location jr to location $j'r'$. Migration costs are exogenous; they vary across location pairs and education levels. The individual-specific random taste shock for moving from location jr to $j'r'$ is denoted by $\xi_{b,s,t}^{jr,j'r'} \in \mathbb{R}$ and follows an i.i.d. type I extreme value distribution with a common scale parameter $\mu > 0$. This scale parameter governs the responsiveness of migration decisions to changes in $w_{s,t}^{j'r'}$ and to $x_{b,s,t}^{jr,j'r'}$. Although $\xi_{b,s,t}^{jr,j'r'}$ is individual specific, we omit individual subscripts for notational convenience.

It should be remembered that the number of new native adults of type s at time t is denoted by $N_{s,t}^{jr}$. Depending on the elevation structure of the location and on the sea level rise, part of the location of birth may be flooded at the beginning of the period. If so, a proportion Θ_t^{jr} of the native-born population is forced to leave. We label the number of forcibly displaced people as $N_{f,s,t}^{jr} = \Theta_t^{jr} N_{s,t}^{jr}$, and the rest of the native population as $N_{d,s,t}^{jr} = (1 - \Theta_t^{jr}) N_{s,t}^{jr}$. Only the latter can decide whether to stay in the area of birth. Hence, those who grew up in the non-flooded area of location jr have the choice between emigrating to another region jr' within the same country (at a cost $x_{d,s,t}^{jr,jr'}$), emigrating to a foreign country (at a cost $x_{d,s,t}^{jr,j'r'}$), or staying. In the last case, they incur no cost associated with moving. This means that $x_{d,s,t}^{jr,jr} = 0$.

By contrast, individuals who grew up in the flooded area have the option to relocate within the same region (from a flooded to a non-flooded area). They incur a welfare loss that corresponds to a fraction $x_{f,s,t}^{jr,jr} > 0$ of their lifetime utility (which is equivalent to an income loss of $x_{f,s,t}^{jr,jr}$ percent in our context). They can also emigrate to another region or to another country at the same cost as those who grew up in the non-flooded area (i.e., $x_{f,s,t}^{jr,j'r'} = x_{d,s,t}^{jr,j'r'}$).

We first focus on *people who grew up in the non-flooded area* (d) of their location of birth. Given their taste characteristics (captured by ξ), each individual chooses the location that maximizes her utility, defined in equation (6). Under the type I extreme value distribution of ξ with a scale parameter μ, McFadden (1974) shows that the probability of choosing region $j'r'$ for individuals originating from region jr is governed by a logit expression. Therefore, the emigration rate is given by

$$\frac{M_{d,s,t}^{jr,j'r'}}{N_{d,s,t}^{jr}} = \frac{\exp\left(\ln\left(w_{s,t}^{j'r'}\left(1 - x_{d,s,t}^{jr,j'r'}\right)\right)^{1/\mu}\right)}{\sum_{kp} \exp\left(\ln\left(w_{s,t}^{kp}\left(1 - x_{d,s,t}^{jr,kp}\right)\right)^{1/\mu}\right)} = \frac{\left(w_{s,t}^{j'r'}\right)^{1/\mu}\left(1 - x_{d,s,t}^{jr,j'r'}\right)^{1/\mu}}{\sum_{kp}\left(w_{s,t}^{kp}\right)^{1/\mu}\left(1 - x_{d,s,t}^{jr,kp}\right)^{1/\mu}}. \tag{7}$$

Hence, emigration rates are endogenous, destination- and skill-specific, and fall between 0 and 1. The choices of emigrating internally or internationally are interdependent. Staying rates ($M_{d,s,t}^{jr,jr}/N_{d,s,t}^{jr}$) are expressed by a similar logit expression.

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It follows that the emigrant-to-stayer ratio ($m^{jr,j'r'}_{d,s,t}$) is governed by:

$$m^{jr,j'r'}_{d,s,t} \equiv \frac{M^{jr,j'r'}_{d,s,t}}{M^{jr,jr}_{d,s,t}} = \left(\frac{w^{j'r'}_{s,t}}{w^{jr}_{s,t}}\right)^{1/\mu} \left(1 - x^{jr,j'r'}_{d,s,t}\right)^{1/\mu}, \tag{8}$$

such that $m^{jr,jr}_{d,s,t} = 1$.

Equation (8) is a gravity-like migration equation, which states that the ratio of emigrants from location jr to location $j'r'$ to stayers in region jr (i.e., individuals born in jr who remain injr) is an increasing function of the wage rate in the destination location $j'r'$ and a decreasing function of the utility in jr. The proportion of migrants from jr to $j'r'$ also decreases with the bilateral migration cost $x^{jr,j'r'}_{d,s,t}$. Labor is not perfectly mobile across sectors/regions; internal migration costs capture all private costs that migrants must incur to move between regions.[4] Similarly, international migration costs capture private costs as well as the legal/visa costs imposed by destination countries. They are also assumed to be exogenous. Heterogeneity in migration tastes implies that emigrants select all destinations for which $x^{jr,j'r'}_{d,s,t} < 1$ (if $x^{jr,j'r'}_{d,s,t} = 1$, the corridor is empty).

Individuals raised in the flooded area of location jr (denoted by the superscript f) are forced to move. If they relocate to the non-flooded area of their region of birthjr, they face a local relocation cost equivalent to $x^{jr,jr}_{f,s,t} > 0$. If they move to another country or region, they will incur the same moving costs as individuals born in the non-flooded area (i.e., $x^{jr,j'r'}_{f,s,t} = x^{jr,j'r'}_{d,s,t}\ \forall jr \neq j'r'$). The local relocation cost influences decisions to emigrate to another region or country. The emigrant-to-stayer ratio ($m^{f}_{r^*r,s,t}$) for forcibly displaced people is governed by:

$$m^{jr,j'r'}_{f,s,t} \equiv \frac{M^{jr,j'r'}_{f,s,t}}{M^{jr,jr}_{f,s,t}} = \left(\frac{w^{j'r'}_{s,t}}{w^{jr}_{s,t}}\right)^{1/\mu} \left(\frac{1 - x^{jr,j'r'}_{d,s,t}}{1 - x^{jr,jr}_{f,s,t}}\right)^{1/\mu}, \tag{9}$$

such that $m^{jr,jr}_{f,s,t} = 1$. In addition, since $x^{jr,jr}_{f,s,t} > 0$, $m^{jr,j'r'}_{f,s,t} > m^{jr,j'r'}_{d,s,t}$, forcibly displaced people are more likely to migrate than those who grew up in non-flooded regions.

For simplicity, we assume that international migrants settle in the urban region of their destination country. This choice is guided by the fact that the data used to calibrate the migration technology do not document the region of destination for international migrants. This means that $m^{jr,j'a}_{b,s,t} = 0$ or, equivalently, $x^{jr,j'a}_{b,s,t} = 1\ \forall j \neq j'$. We can define the ratio of international emigrants to stayers as:

$$m^{jr,F}_{b,s,t} \equiv \sum_{j' \neq j} m^{jr,j'n}_{b,s,t}, \tag{10}$$

Once emigrant-to-stayer ratios are determined, we can characterize the equilibrium structure of the resident labor force in (the non-flooded area of) all regions and by education level. We thus have:

$$L^{jr}_{s,t} = \sum_{b,j',r'} \frac{m^{j'r',jr}_{b,s,t} N^{j'r'}_{b,s,t}}{1 + m^{j'r',j'r}_{b,s,t} + m^{j'r',jr}_{b,s,t}}. \tag{11}$$

[4]In line with Young (2013), internal mobility is driven by self-selection (i.e., skill-specific disparities in utility across regions as well as heterogeneity in unobserved individual characteristics).

2.3 Dynamics and intertemporal equilibrium

The dynamics of the native population are governed by fertility and education decisions. In contrast to Burzyński *et al.* (2020) and Burzyński *et al.* (2019), we assume that these decisions are exogenous. We use $n_{s,t}^{jr}$ to denote the number of children of parent of type s living in (the non-flooded area of) location jr at time t. We denote by $p_{s,t}^{jr}$ the proportion of children acquiring a college education. It follows that the dynamic structure of the model is totally recursive. Accordingly, we have:

$$\begin{cases} N_{h,t+1}^{jr} = \sum_{s,b} L_{s,t}^{jr} n_{s,t}^{jr} p_{s,t}^{jr} \\ N_{l,t+1}^{jr} = \sum_{s,b} L_{s,t}^{jr} n_{s,t}^{jr} (1 - p_{s,t}^{jr}) \end{cases} \tag{12}$$

An inter-temporal equilibrium for the world economy can be defined as follows:

Definition 1 *For a set* $\{\mu, \gamma, \sigma_r, \epsilon_r, \kappa_r\}$ *of common parameters, a set of location-specific exogenous characteristics* $\{\bar{A}_t^{jr}, \bar{\eta}_t^{jr}, \Theta_t^{jr}, n_{s,t}^{jr}, p_{s,t}^{jr}, x_{b,s,t}^{jr,j'r'}\}$*, and a set* $\{N_{s,0}^{jt}\}$ *of predetermined variables, an intertemporal competitive equilibrium is a set of endogenous variables* $\left\{w_{s,t}^{jr}, A_{r,t}, \eta_t^{jr}, m_{d,s,t}^{jr,j'r'}, m_{f,s,t}^{jr,j'r'}, L_{s,t}^{jr}, N_{s,t+1}^{jr}\right\}$*, that simultaneously satisfies profit maximization conditions and technological constraints (2), (4) and (5), utility maximization conditions (8) and (9) in all countries and regions of the world, and such that the equilibrium structure and dynamics of population satisfy equations (11) and (12).*

2.3 Caveats and value added

Our model inevitably omits a number of features. First, it abstracts from *physical capital* accumulation. Assuming production is proportional to labor expressed in efficiency units is equivalent to assuming a constant capital-to-labor ratio [i.e., Burzyński *et al.* (2020); Delogu *et al.* (2018); Kennan (2013); Klein and Ventura (2009)]. Such a condition holds in the context of a small open economy with perfect mobility of capital between countries and regions, or on the long-run balanced growth path of a closed economy model. This assumption is in line with the time structure of our model (one period represents about 30 years), acknowledging that we disregard the effects induced by potential variations in the worldwide level of the capital-to-labor ratio.

Second, the model abstracts from *trade*. Assuming that firms in the two sectors produce the same good, the model disregards variations in the relative price of the agricultural good. In a context with heterogeneous goods, variations in the relative price of the agricultural good would mitigate or reinforce the urbanization process. In their benchmark scenario, Desmet and Rossi-Hansberg (2015) show that changes in relative prices are small. In addition, Burzyński *et al.* (2020) show that migration and inequality responses to various types of shocks are quantitatively similar when considering that agricultural and non-agricultural goods are identical or imperfect substitutes as in Boppart (2014).

Third, we assume that *fertility and education* decisions are exogenous, which basically means that the dynamics of the size and structure of before-migration populations are assumed to be independent of climate change. Richer results with endogenous population movements can be found in a companion working paper [Burzyński *et al.* (2019)], where the deterministic part of the RUM is itself an

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outcome of a (second-stage) utility-maximization problem over consumption, fertility, and education. These simulations reveal that socio-demographic responses to climate changes are small.

3. Parameterization

Our model is calibrated for 179 countries accounting for more than 99% of the world population. Our parameterization strategy involves three steps. First, we calibrate common and location-specific parameters in order to (perfectly) match socio-demographic and economic moments for the year 2010 (referred to as the year 0 below) or for the period 1980–2010. The set of socio-demographic moments includes internal and international migration flows. Second, we define a socio-demographic trajectory for the twenty-first century that is in line with official projections of population, urbanization, and human capital. Third, we describe our climate damage functions under three climate scenarios.

Matching the current state of the world: We collect data on the socio-demographic and economic characteristics of 179 countries in 1980 and 2010. We use data on Gross Domestic Product (GDP) from the United States Department of Agriculture (USDA) and the proportion of agricultural production in value added from the Food and Agriculture Organization of the UN (FAOSTAT). This determines Y_0^{jr}. For the structure of the resident labor force by education level and by sector ($L_{s,0}^{jr}$), we use the estimates described in Burzyński *et al.* (2020). Data on wages by education level ($w_{s,0}^{jr}$) are obtained from Biavaschi *et al.* (2020) for the non-agricultural sector and from the Gallup World Polls for the agricultural sector. We extract the dyadic numbers of international migrants by education level for 2010 from the Database on Immigrants in OECD and non-OECD countries. Within each country, we split the number of emigrants by region of origin and education level, assuming that the structure of migration aspirations (obtained from the Gallup World Polls) is identical to the structure of actual emigration stocks. This gives $M_{s,0}^{jr,j'r'}$.

With regard to technological parameters are concerned, we calibrate the elasticity of substitution between college graduates and less educated workers (σ^r), relying on existing studies. For the non-agricultural sector we follow Ottaviano and Peri (2012), who suggest setting the elasticity close to 2, whereas for the agricultural sector, it is usually assumed that the substitution is perfect [e.g., Lucas (2009); Vollrath (2009)]. Using equation (3), we then calibrate the skill-bias term, η_t^{jr}, so as to match the observed income ratio between skill groups. Using equation (1), we calibrate the TFP level, A_0^{jr}, in order to match the observed level of GDP. Regressing the logs of η_0^{jr} and A_0^{jr} on the log of the skill ratio, we identify the size of the technological externalities (ϵ^randκ^r). Last, $\bar{A}^{jr}$ and $\bar{\eta}^{jr}$ are identified as residuals from equations (4) and (5).

With regard to the migration technology, Bertoli and Fernández-Huertas Moraga (2013) find a value between 0.6 and 0.7 for the migration elasticity to income disparities, captured by $1/\mu$ in our model. Hence, we use $\mu = 1.4$. We obtain international and internal migration costs ($x_{s,0}^{jr,j'r'}$) as residuals from equation (8). As climate change is expressed in terms of deviations from the current state of the world, we do not account for any climate change-related flooded areas in the year 2010. For internal migration costs, we assume positive migration from rural to urban regions (i.e., $x_{s,0}^{ja,jn} < 1$), but no migration from urban to rural region ($x_{s,0}^{jn,ja} = 1$). For local

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migration costs in flooded areas, we pessimistically assume $x_{f,s,t}^{jr,jr} = 0.5$ (i.e., relocating within the location where a person was born induces an income loss equal to 50% of the lifetime utility), in line with literature on conflict-related displacements [e.g., Fiala (2015); Ibáñez and Moya (2006); Kellenberg and Mobarak (2011)]. Using a similar parameterization strategy, Burzyński *et al.* (2020) predict variations in the dyadic stocks of migrants between 1950 and 1980 and obtain a close fit to the observed values.

Socio-demographic environment: Unless otherwise stated, we assume constant migration costs over the twenty-first century (i.e., $x_{s,t}^{jr,j'r'} = x_{s,0}^{jr,j'r'} \forall t$). For $n_{s,t}^{jr}$ and$p_{s,t}^{jr}$, we use the projections of Burzyński *et al.* (2020), who endogenize the trajectory of socio-demographic variables in a similar overlapping generations framework without climate change. They constrain their baseline trajectory to be compatible with medium-term official demographic projections, as reflected by the UN projections of the national adult population and the proportion of college graduates for 2040. This can be achieved by assuming a process of quadratic convergence in access to education. This implies that middle-income countries converge towards high-income countries, while low-income countries diverge or converge less rapidly. For subsequent years and in all climate variants, we assume a continuation of this quadratic convergence process. The resulting changes in the size and structure of the population partly determine the skill ratio and the level of the technology in all locations.

Climate scenarios: Our climate scenarios involve temperature changes and rising sea levels. Temperature and sea level projections are available from the CCKP portal [Taylor *et al.* (2012)], which distinguishes between several emissions scenarios labeled as representative concentration pathways (RCP) [Moss *et al.* (2010)]. They are organized in 20-year climatological windows. The median-emissions scenario is termed *RCP-4.5*, which predicts that emissions will peak around 2040 before declining. For each RCP, the CCKP provides data for 16 models obtained from different research institutes. When these 16 models are ranked in ascending order according to the secular temperature variation, the medium resolution model of the Institute Pierre Simon Laplace (the *ipsl_cm5a_mr* variant) takes the eighth (median) position in *RCP-4.5*. We select this "median of the medians" variant as our baseline scenario and consider three alternative scenarios:

- No climate change (*No CLC*): No change in temperature and in sea levels. Most probably unattainable, this scenario serves as the no climate change reference.
- Baseline (*RCP-4.5*): Median temperature scenario corresponding to the median emissions scenario (*RCP-4.5*). This baseline involves mean increases in temperature and sea levels of 1.8 °C and 0.47 m, respectively.
- Higher temperature (*Higher T*): Starting from the baseline, we double the predicted changes in temperature in all regions, keeping the rise in the sea levels identical to that used in the baseline.
- Higher sea levels (*Higher SL*): Starting from the baseline, we double the predicted rise in the sea levels in all parts of the world, keeping temperature changes identical to those used in the baseline.

Projections of temperature and changes in sea levels by pixel of 1 km × 1 km can be obtained from Giorgetta *et al.* (2012). With regard to temperature, and for the baseline, Figure 1(a) illustrates the predicted variations in temperature between 2010 and 2100 by latitude and longitude. The largest variations are observed in the extreme north as well as some regions located close to the equator and in the east. Similarly, global changes to sea levels will not be uniform, but will exhibit substantial regional deviations [Oppenheimer *et al.* (2019)]. Thermal expansion, ocean dynamics, and land ice loss contributions will generate regional departures from the global mean sea-level rise of about ±30%. Figure 1(b) shows that the rise in sea levels will be more pronounced in the extreme north, in the northern part of the Atlantic Ocean, and in the south-east of the Cape of Good Hope. This determines the surface of flooded areas. In order to account for such heterogeneities, we combine sea level projection data by pixel with high-resolution, geo-referenced information on topography [Tadono *et al.* (2014)] and distance to coastlines [Stumpf (2012)].

Climate damage functions: To predict the long-term implications of climate change, we consider two mechanisms of transmission. First, we allow changes in the mean level of temperature to affect productivity, expected income, and incentives to migrate [as in Dallmann and Millock (2017); Desmet and Rossi-Hansberg (2015); Shayegh (2017)]. Second, we model forced displacements linked to rises in sea levels [as in Desmet *et al.* (2018); Rigaud *et al.* (2018)].[5]

To model the effect of temperature, we follow Desmet and Rossi-Hansberg (2015), who estimate the relationship between temperature and TFP in agricultural and manufacturing sectors. This function corresponds to $G(T_t^{jr})$ in equation (4). The curve is inverted-U-shaped for both sectors but flatter in manufacturing. Desmet and Rossi-Hansberg (2015) find an optimal temperature of 21.1 °C for agriculture, and 17.4 °C for non-agriculture. The level of TFP increases with temperatures in regions with average temperatures below these optimal levels; it decreases with temperature in warmer regions.

It is important to note that our two-sector model does not distinguish between pixels and only establishes a difference between rural/agricultural and urban/non-agricultural regions within each country. Climate literature suggests that temperature levels observed at the centroid of each country may not accurately reflect the impact of climate change. This may be due to the fact that aggregate measurements poorly capture population concentration and individuals' average exposure to temperature change in large countries with regions of heterogeneous population densities. Hence, we use population-weighted changes in temperature from Dell *et al.* (2012). Figures 1(c) and 1(e) show the direct effect of temperature on agricultural and non-agricultural TFP levels for each country and for the year 2100. On average, in the *RCP-4.5* scenario, agricultural productivity decreases by 20–25% in countries close to the equator and increases by the same amount at high latitudes. Similarly, non-agricultural productivity

[5]The slow-onset mechanisms considered in this paper are foreseeable and likely to induce adaptation strategies such as crop switching (which is implicitly taken into account in the $G(T_t^{jr})$ damage functions) and migration. The companion working paper [Burzyński *et al.* (2019)] supplements these damage functions with additional mechanisms related to fast-onset climate shocks. This allows us to connect the distribution of daily temperature with the frequency of natural disasters as well as with productivity and health costs. These fast-onset mechanisms affect all countries by similar intensities, and barely have any impact on interregional and international migration responses. The working paper version also accounts for conflicts over resources and concludes that climate-related conflicts could become a key component of future climate migration pressures. However, predicting the occurrence of conflicts and the number of countries involved is a complex task. Hence, in this paper, we focus on slow-onset mechanisms only.

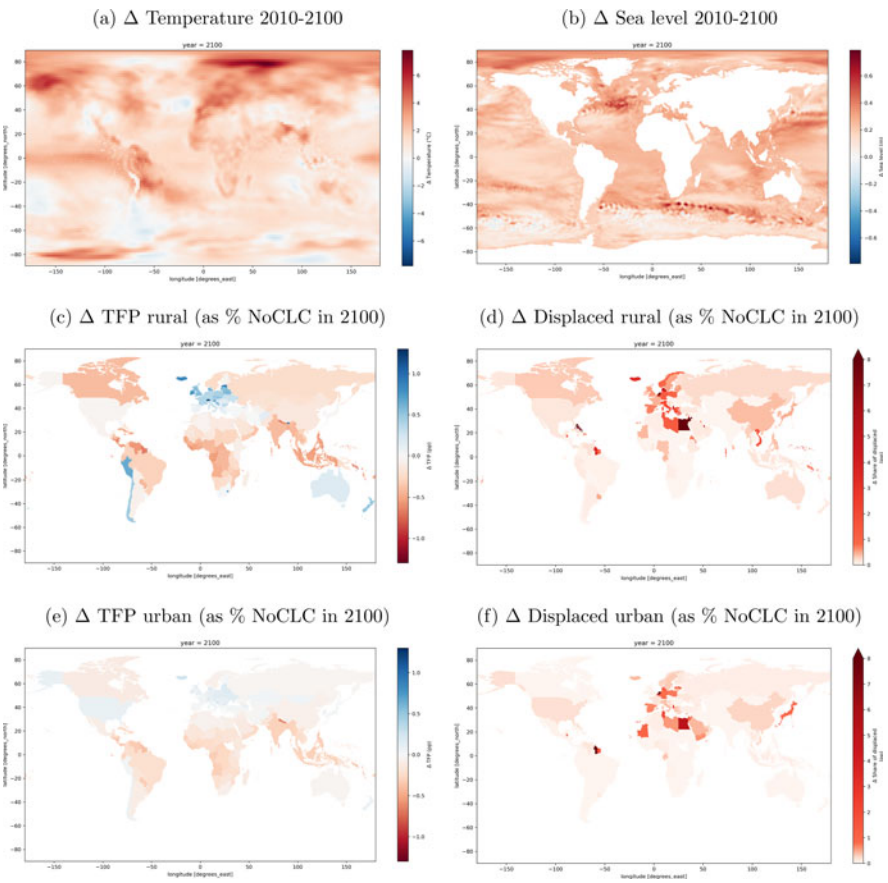

Figure 1. *RCP-4.5* scenario and its effects on TFP and forced displacement.
Notes: Own calculations based on climate data by Giorgetta *et al.* (2012). Subfigures (a) and (b) represent deviations from the baseline situation in 2010 at the pixel level. Subfigures (c)–(f) represent relative deviations from the NoCLC scenario in the year 2100 and at the region level.

decreases by 10–15% in countries close to the equator, and increases slightly at high latitude levels.

This implies that climate change will affect income convergence over the twenty-first century. From equation (4), it appears that TFP levels are also affected by changes in the skill ratio (z_t^{jr}), which result from our (exogenous) socio-demographic hypotheses and (endogenous) migration outcomes. For each climate scenario and sector, we can run a cross-country regression of the mean annual growth rate of TFP over the twenty-first century on its initial level (in logs). The results of these beta-convergence regressions are illustrated in Figure 2. The left-hand panel gives the results obtained for agriculture (each country is represented by a red bubble), while the right-hand panel shows the results for non-agriculture (each country is represented by a blue bubble).

In the *No CLC* scenario (top panel), we abstract from climate change. The beta-convergence regression results are governed by the assumed quadratic convergence process in human capital formation (i.e., in domestic investment in

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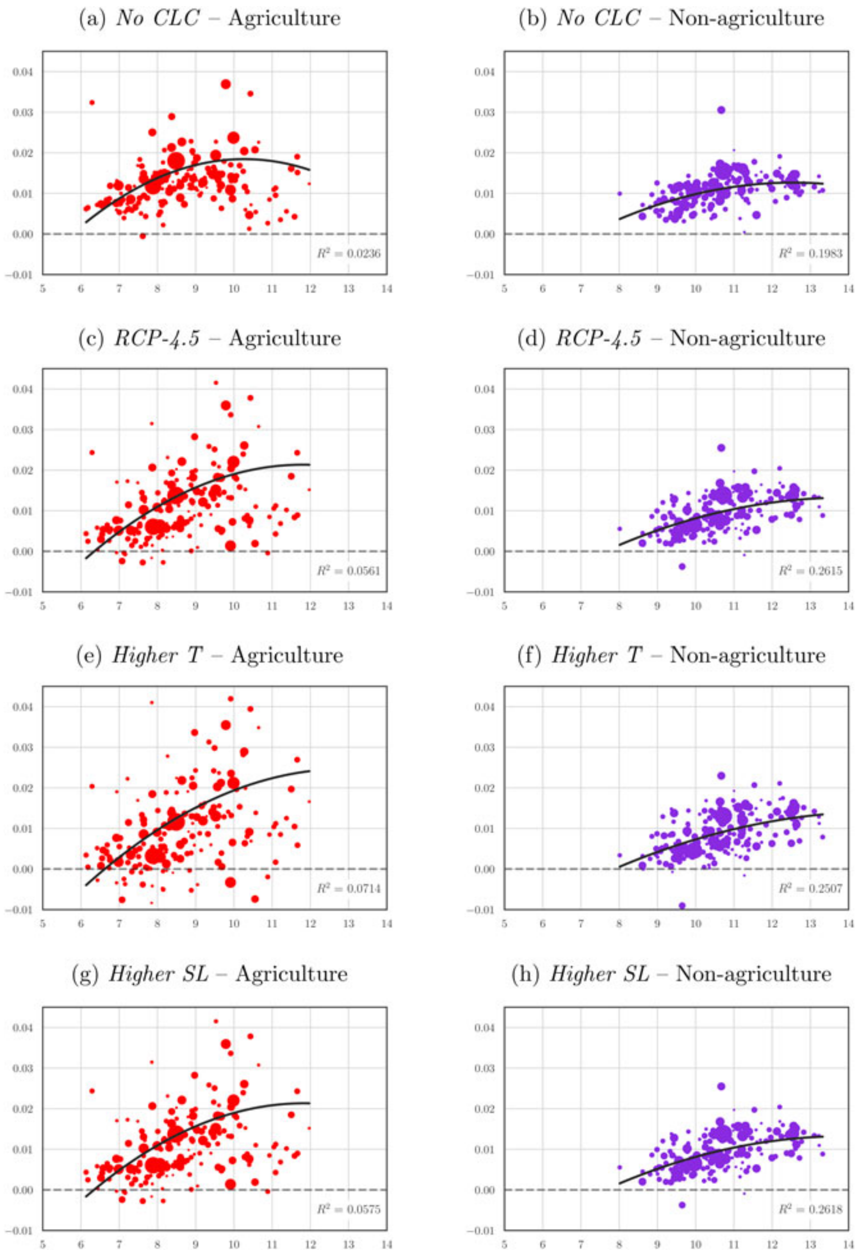

Figure 2. Convergence vs. divergence in TFP under alternative climate scenarios.

Notes: Mean annual growth rates of TFP levels over the period 2010–2100 are represented on the vertical axes. The 2010 levels of TFP (in logs) are represented on the horizontal axes. The trends correspond to the quadratic relationship between the two variables. A negative slope indicates a convergence process; a positive slope indicates divergence.

education). In line with the median socio-demographic scenario of the United Nations, our socio-demographic environment assumes that progress in education is greater in middle-income countries than in rich and in poor countries. The resulting effect on the skill ratio and TFP is reinforced by internal and international mobility responses —people moving from low-productivity to high-productivity regions and countries. Hence, this scenario implies quadratic convergence in TFP levels. Roughly speaking, in both sectors, TFP levels converge among countries and regions belonging to the top quartile of the initial TFP distribution. Countries and regions below the top quartile diverge.

The convergence implications of climate change are illustrated in the bottom panels in Figure 2. Under the *RCP-4.5* scenario, the divergence forces are strengthened. Variations in temperature will induce dramatically different effects on productivity in countries above and below the 35th parallel. Over the twenty-first century, agricultural productivity decreases by 20–25% in countries close to the equator, and increases by 10–15% at high latitudes. Non-agricultural productivity decreases by 10–15% in countries close to the equator, and slightly increases at high latitudes. Over the twenty-first century, the annual growth rate of TFP is 2 percentage points higher in the wealthiest regions compared with the poorest ones. Hence, low-latitude countries in general, and their rural regions in particular, will be the most adversely affected by climate change. The magnitudes of these effects are greater when temperature variations are doubled (see *Higher T*), whereas higher sea level rise has almost no impact on TFP convergence (see *Higher SL*).

We now turn our attention to forced displacements, which are predicted by combining sea level projection data from Giorgetta *et al.* (2013) with high-resolution geo-data on population density [CIESIN-Columbia University (2018))] and data on the rural/urban divide from Balk *et al.* (2006). Our approach by pixel enables us to proxy the number of individuals at risk from coastal flooding on a 1 km × 1 km grid and by region. Coupling this information with data on the geographical extent of urban/rural areas [Balk *et al.* (2006)] allows us to compute the fraction of population affected by rises in sea levels (Θ_t^{jr}) by country.

Figures 1(d) and 1(f) give the total number of displaced persons over the twenty-first century in rural and urban regions, respectively. Rising sea levels mostly affect countries where a large proportion of the population is located along the coasts of seas and oceans, or in the major river deltas. The proportion of displaced persons is large in South Asian and East Asian countries. Some Pacific islands situated a few centimeters above sea level (e.g., Tuvalu, Kiribati) are in a position of extreme vulnerability. Wealthy and poor countries will be equally adversely affected by rising sea levels.

4. Results

As the relationship between temperature and productivity is nonlinear and sector specific, climate change increases income disparities between and within countries. Table 1 summarizes the macroeconomic implications of climate change for the world and by region. The bottom lines of this table show the worldwide responses, computed as the weighted averages of the positive and negative effects observed in high-income and developing countries. The values shown in bold are the projections obtained in the *No CLC* scenario. The values underneath are the variations induced

Table 1. Aggregate effects of climate change by world region

		GDP in billions $US			GDP per worker			HS share in %			Population in millions			Urban Share in %		
Regions	Scenario	2040	2070	2100	2040	2070	2100	2040	2070	2100	2040	2070	2100	2040	2070	2100
CARE	No CLC	836.52	952.07	990.09	7,662.72	8,743.64	10,508.80	17.84	20.92	25.13	109.17	108.89	94.22	38.67	39.90	42.75
	ΔRCP-4.5	−74.70	−125.21	−157.88	−664.52	−1,085.33	−1,535.13	−0.08	−0.09	−0.09	−0.31	−0.92	−1.48	0.40	0.71	0.95
	ΔHigher T	−110.48	−184.78	−233.67	−980.04	−1,593.53	−2,258.36	−0.13	−0.15	−0.13	−0.52	−1.58	−2.54	0.69	1.24	1.67
	ΔHigher SL	−73.85	−127.46	−157.72	−654.77	−1,098.64	−1,521.88	−0.09	−0.19	−0.07	−0.34	−1.03	−1.60	0.59	0.85	1.08
EAP	No CLC	1,942.72	2,177.94	2,155.79	20,035.55	26,532.65	33,785.23	15.93	21.29	27.02	96.96	82.09	63.81	60.68	68.00	72.97
	ΔRCP-4.5	−106.62	−164.26	−192.35	−1,054.30	−1,781.73	−2,471.52	−0.09	0.00	0.13	−0.23	−0.73	−1.11	0.84	1.31	1.53
	ΔHigher T	−158.84	−243.90	−286.27	−1,569.33	−2,633.58	−3,649.22	−0.14	0.02	0.23	−0.36	−1.16	−1.77	1.34	2.15	2.54
	ΔHigher SL	−106.66	−163.39	−192.28	−1,055.66	−1,773.07	−2,474.02	−0.09	0.02	0.13	−0.22	−0.73	−1.10	0.82	1.30	1.52
LAC	No CLC	1,042.78	1,144.39	1,116.01	43,390.24	53,409.78	65,117.75	32.31	37.90	43.59	24.03	21.43	17.14	84.93	88.17	90.43
	ΔRCP-4.5	−75.32	−116.12	−132.17	−2,887.53	−4,743.00	−6,423.89	−0.01	0.07	0.20	−0.14	−0.30	−0.38	0.15	0.27	0.37
	ΔHigher T	−112.64	−173.28	−196.92	−4,311.65	−7,071.77	−9,576.80	−0.02	0.11	0.32	−0.23	−0.47	−0.59	0.26	0.47	0.63
	ΔHigher SL	−75.37	−116.82	−132.12	−2,871.56	−4,757.16	−6,408.24	−0.01	0.03	0.21	−0.15	−0.31	−0.38	0.17	0.28	0.38
MENA	No CLC	856.98	1,063.70	1,146.50	30,320.61	34,118.02	40,103.99	28.98	31.41	35.03	28.26	31.18	28.59	67.97	66.24	66.43
	ΔRCP-4.5	−29.06	−51.15	−66.67	−1,154.46	−1,660.93	−2,181.15	0.00	0.03	0.24	0.13	0.02	−0.12	0.61	0.87	1.13
	ΔHigher T	−42.48	−73.61	−97.66	−1,721.14	−2,441.56	−3,246.45	−0.01	0.09	0.37	0.22	0.08	−0.13	0.92	1.36	1.76
	ΔHigher SL	−28.85	−50.90	−66.47	−1,159.63	−1,678.56	−2,199.53	0.00	0.04	0.23	0.14	0.04	−0.10	0.56	0.83	1.08
OECD	No CLC	10,217.85	9,862.12	9,436.58	177,786.86	208,568.07	244,574.22	56.17	60.87	64.94	57.47	47.28	38.58	85.79	89.73	92.75
	ΔRCP-4.5	266.35	417.75	518.11	2,749.90	4,819.73	6,519.89	−0.07	−0.18	−0.21	0.60	0.89	1.07	0.16	0.18	0.17
	ΔHigher T	426.47	682.37	831.63	4,385.09	7,898.26	10,417.02	−0.12	−0.25	−0.34	0.96	1.43	1.69	0.29	0.33	0.29
	ΔHigher SL	271.39	416.34	518.08	2,761.12	4,840.04	6,554.72	−0.08	−0.19	−0.21	0.63	0.88	1.06	0.18	0.19	0.18
SSA	No CLC	403.55	781.45	1,311.88	6,950.25	7,587.66	7,879.56	4.97	5.47	5.52	58.06	102.99	166.49	38.98	39.34	38.75

	ΔRCP-4.5	−11.27	−52.06	−122.62	−189.83	-482.73	−678.33	−0.02	−0.05	-0.05	-0.03	−0.33	−1.34	0.12	0.41	0.63
	ΔHigher T	−16.79	−77.50	−182.50	−282.42	−716.77	−1,005.49	−0.03	−0.07	−0.07	-0.06	−0.54	−2.19	0.20	0.68	1.06
	ΔHigher SL	−11.28	−52.07	−122.63	−189.81	−482.57	−678.01	−0.02	−0.05	−0.05	-0.04	−0.33	−1.35	0.13	0.41	0.63
World	No CLC	15,300.40	15,981.68	16,156.84	40,914.18	40,577.94	39,520.13	23.01	23.51	22.66	373.96	393.85	408.83	56.85	56.30	54.21
	ΔRCP-4.5	−30.61	−91.05	−153.56	−81.83	-90.92	−51.69	0.00	0.04	0.11	0.00	−1.36	−3.36	0.49	0.77	0.93
	ΔHigher T	−14.76	−70.71	−165.39	−39.42	51.04	132.66	0.00	0.09	0.18	0.00	−2.23	−5.54	0.80	1.28	1.56
	ΔHigher SL	−24.61	−94.31	−153.12	−65.76	−89.14	−39.82	0.00	0.02	0.11	0.00	−1.46	−3.47	0.54	0.81	0.96

Notes: This table depicts our aggregated projections of income and population indicators for the *No CLC* scenario and contrasts them with the *RCP-4.5*, *Higher T*, and *Higher SL* scenarios. For example, Δ*RCP-4.5* = *RCP-4.5* − *No CLC*. Regions: Central Asia and the Rest of Europe (CARE), East Asia and Pacific (EAP), Latin America and Caribbean (LAC), Middle East and North Africa (MENA), OECD, Sub-Saharan Africa and the world. Population counts refer to those aged 25 years and above.

by the *RCP-4.5*, *Higher T*, and *Higher SL* scenarios, expressed as deviations from the *No CLC* scenario.

In a nutshell, we find that climate change barely affects the worldwide average level of GDP per worker, but does make its distribution more unequal. Under the *RCP-4.5* scenario, the worldwide level of GDP per worker decreases by 0.2%, 0.2%, and 0.1% in 2040, 2070, and 2100, respectively. Similar changes are obtained under the *Higher SL* scenario. Under the *Higher T* scenario, the worldwide loss is even smaller in 2040 (−0.1%) and turns into a small gain in 2070 (+ 0.1%) and in 2100 (+ 0.3%). There are two reasons for aggregate GDP effects being small and potentially positive. First, higher temperature levels induce positive changes in TFP at high latitudes (where income per worker is initially higher) and negative changes in TFP close to the equator (where income per worker is initially lower). Second, climate change reallocates people from poorer to richer countries and regions. As movers adopt the fertility and education norms of the destination country/region, climate change increases the worldwide average proportion of college graduates and reduces the size of the world's working-age population. It is worth noting that the utility costs of these movements are not accounted for in our GDP responses to climate change, nor are unpredictable income losses due to extreme weather events. This implies that we can expect a (larger) decrease in global welfare.

When looking at the region-specific effects, climate change increases GDP per worker in OECD countries only; the effects in 2040, 2070, and 2100 amount to 1.5%, 2.3%, and 2.7%, respectively, under the *RCP-4.5* scenario, and to 2.5%, 3.8%, and 4.3%, respectively, under the *Higher T* scenario. By contrast, climate change decreases GDP per worker in developing regions despite the fact that it reallocates some people from lower-productivity rural regions to higher-productivity urban regions. The losses are important. In sub-Saharan Africa, the poorest region of the world, the effects amount to −2.7%, −6.4%, and −8.6% in 2040, 2070, and 2100, respectively, under the *RCP-4.5* scenario, and by −4.1%, −9.4%, and −12.8%, respectively, under the *Higher T* scenario. In relative terms, similar losses are obtained in East Asian and Pacific countries, as well as in the Middle East and Northern Africa. Larger long-term effects are obtained in Central Asia (−21.5%) and in Latin America (−14.7%) in the *Higher T* scenario.

Climate change thus creates conditions that are conducive to increasing urbanization and international migration from developing countries and regions to high-income ones. In section 4.1, we quantify the number of climate migrants per period and characterize the geography of these movements. Section 4.2 identifies some notable country-specific implications. The effect of climate change on urbanization is discussed in section 4.3. Then, section 4.4 investigates the skill structure of climate migration. The rest of the section focuses on the poverty implications of climate change and on the role of migration policies (section 4.5).

4.1 Climate migrants worldwide

The migration implications of climate change are presented in Figure 3 and summarized in Table 2. The top panel of Table 2 gives the benchmark number of movers obtained in the absence of any climate change, distinguishing between local movements (nil under a constant sea level), inter-regional, and international movements. For the latter, we classify these as North–North (N–N), North–South (N–S), S–N and S–S. Countries from the North are meant to represent high-income

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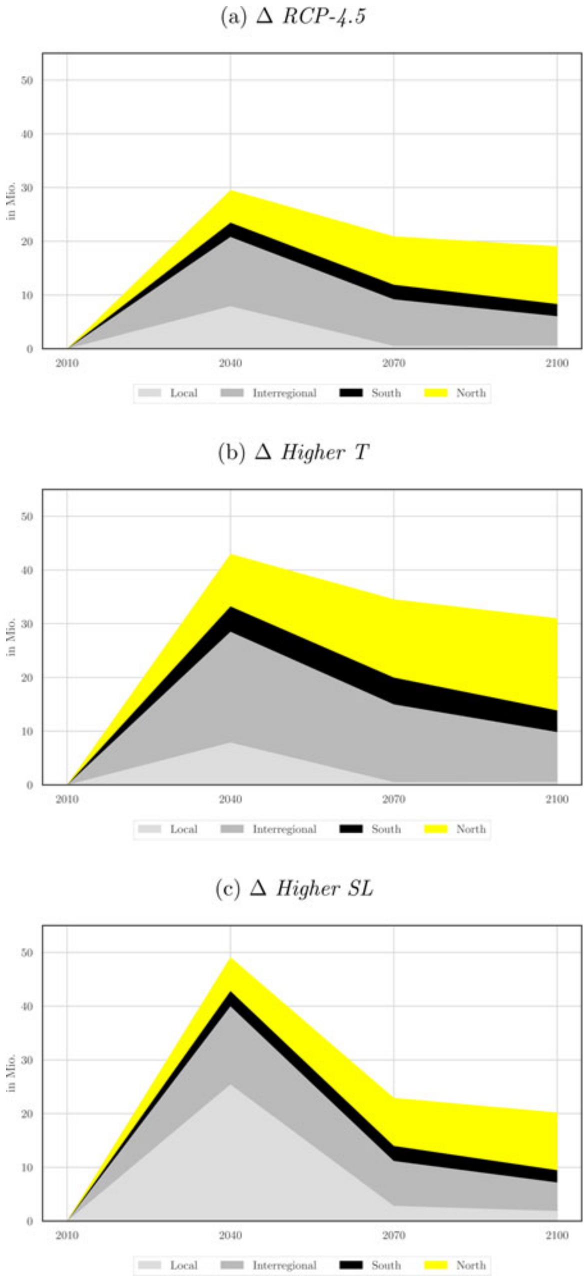

Figure 3. Climate migration worldwide.

OECD countries. The next two panels give the number of additional climate migrants predicted under the two climate scenarios. In the *RCP-4.5* scenario, we identify 29.5, 20.9, and 19.1 million climate migrants in 2040, 2070, and 2100, respectively. This

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Table 2. Climate migration worldwide (in millions)

		Local	Int-reg	N–N	N–S	S–N	S–S	Total
No CLC	2040	0.00	461.5	47.0	3.1	127.0	112.2	–
	2070	0.0	437.3	31.7	2.1	142.4	131.6	–
	2100	0.0	433.9	20.4	1.4	149.3	145.1	–
ΔRCP-4.5	2040	7.9	12.9	0.2	−0.1	5.9	2.8	29.5
	2070	0.5	8.7	0.0	−0.1	9.0	2.8	20.9
	2100	0.6	5.5	0.0	−0.1	10.7	2.4	19.1
	Total	9.0	27.1	0.2	−0.3	25.6	7.9	69.5
ΔHigher T	2040	7.9	20.6	0.3	−0.1	9.5	4.8	43.0
	2070	0.5	14.5	0.1	−0.2	14.5	5.2	34.6
	2100	0.6	9.3	−0.0	−0.1	17.2	4.2	31.0
	Total	9.0	44.4	0.3	−0.4	41.1	14.2	108.5
ΔHigher SL	2040	25.4	14.5	0.1	−0.1	6.2	2.9	49.1
	2070	2.8	8.4	0.1	−0.1	8.9	2.9	22.9
	2100	1.9	5.3	0.0	−0.1	10.7	2.4	20.2
	Total	30.1	28.2	0.2	−0.3	25.8	8.2	92.2

corresponds to a total of 69.5 million migrants aged 25 years and above over the course of the twenty-first century. Adding dependent children gives a total number of ∼130 million movers. These estimates are close to those obtained by Rigaud *et al.* (2018), although we use a radically different approach.

Our model allows us to endogenize the preferred destinations of these climate migrants, assuming that migration costs and policies remain constant. Summing up over the three periods, climate change has negligible impacts on N–N and N–S migration, and a small impact on S–S international movements (the black area in Figure 3). Under the *RCP-4.5* scenario (panel (a) in Figure 3), 13% of climate-related moves are local (forced displacements) and 39% are inter-regional (rural to urban); these internal movements are depicted by the light gray and dark gray areas in Figure 3. In addition, long-haul movements from developing to OECD countries (roughly corresponding to the yellow areas in Figure 3, as N–N movements are negligible) account for 37% of climate migration. S–N climate migration involves 25.7 million people over the twenty-first century (i.e., about 8.5 million per period). On average, this represents an increase by 5–7% in the total number of immigrants to OECD countries depending on the period. The rise in sea levels will have the most significant effects between 2010 and the middle of the century. By the year 2040, the projected number of climate migrants reaches 29.5 million people, including 27% of local movements, 44% of inter-regional movements, and 20% of S–N migrants. S–S migration involves 2.8 million movers (9% of the total).

In the *Higher T* scenario, we predict 43.0, 34.6, and 31.0 million adult migrants in 2040, 2070, and 2100, respectively, which corresponds to a total of 108.5 million individuals over the course of the twenty-first century (i.e., 39.0 million more than under the *RCP-4.5* scenario). Adding dependent children brings this number up to around 200 million movers. Over the century, we now find that 8% of climate-related moves are local, 41% are inter-regional, and 38% are S–N. In total, S–N climate migration involves 41.1 million people over the twenty-first century, which represents about 13 million per period. On average, this induces a 7–11% increase in the total number of immigrants to OECD countries depending on the period. By the 2040, the number of climate migrants reaches 43.0 million people, including 18% of local movements, 48% of inter-regional movements, and 22% of S–N migrants. S–S migration involves 4.8 million movers (11% of the total).

There is great uncertainty about the extent of the rise in sea levels because the dynamics of ocean heat uptake as well as the creation and decay of ice sheets and glaciers are poorly understood. It is thus important to examine whether our results are robust to the magnitude of sea level rise. In the *Higher SL* scenarios, we double the sea level rise compared with *RCP-4.5*. This scenario is represented in panel (c) of Figure 3 and in Table 2. This scenario induces movements of 49.1, 22.9, and 20.2 million climate migrants in 2040, 2070, and 2100, respectively. This corresponds to a total of 92.2 million migrants over the course of the twenty-first century (i.e., 22.2 million more than under the *RCP-4.5* scenario). Over the century, 33% of climate-related moves are local and 31% are inter-regional. Compared with the *RCP-4.5* scenario, doubling the magnitude of the sea level rise increases local movements by 21.1 million people, while it only increases rural-to-urban migration by 1.2 million people. Sea level rise has negligible impacts on N–N and N–S migration, and a small impact on S–S international movements. Long-haul movements from developing to OECD countries account for 28% of climate migration. Hence, S–N climate migration now involves 25.8 million people over the twenty-first century; only 0.2 million more than under the *RCP-4.5* scenario.

Our results suggest that forced displacements due to sea level rise are mostly local (i.e., from flooded to non-flooded areas within the same region), while inter-regional and international mobility responses are overwhelmingly governed by the TFP responses to temperature changes.

4.2 Country-specific effects

Table 3 translates our international migration projections into country-specific emigration rates (left-hand panel) and immigration rates (right-hand panel). Emigration rates are expressed as the ratio of the number of international emigrants to the native population aged 25–65 years in the country of origin. Immigration rates are expressed as the ratio of foreigners to the total population aged 25–65 years in the destination countries. In each panel, the first four columns give the evolution of migration rates in the *No CLC* scenario; the next three columns give the variation in migration rates induced by climate change in the *RCP-4.5*, *Higher T*, and *Higher SL* scenarios, respectively. Countries are ranked in decreasing order, according to the variation obtained in the *RCP-4.5* scenario.

The left-hand panel lists the 30 countries exhibiting the largest climate-driven variations in international emigration rates by the end of the century. These mostly include small countries and developing island states located in the Pacific, Caribbean, and Central American regions. Hence, although the variation in emigration rates is substantial (e.g., + 8.3 percentage points in Micronesian islands in the *RCP-4.5* scenario, and + 14.4 percentage points in the *Higher T* scenario), the number

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Table 3. Effect of climate change on migration rates

	Average emigration rate (% of natives)								Average proportion of foreigners (% of residents)						
	No CLC				RCP-4.5	Higher T	Higher SL		No CLC				RCP-4.5	Higher T	Higher SL
Orig.	2010	2040	2070	2100	2100	2100	2100	Dest.	2010	2040	2070	2100	2100	2100	2100
FSM	35.93	35.37	34.12	34.21	8.31	14.40	8.09	ISL	13.44	23.68	34.63	49.32	2.52	3.89	2.51
STP	36.68	45.22	49.04	52.16	7.94	14.54	7.94	USA	25.14	43.84	49.88	54.64	2.38	3.65	2.38
SLV	34.69	43.94	45.27	46.39	7.71	12.88	7.76	BEL	27.61	41.90	54.19	68.67	1.68	2.62	1.68
GUY	55.58	64.16	63.54	66.36	7.22	12.74	7.16	DNK	16.71	24.99	33.02	41.62	1.67	2.58	1.66
CAN	9.70	28.07	29.34	30.54	6.56	11.67	6.56	ITA	15.03	27.93	35.33	44.20	1.65	2.62	1.71
SUR	49.15	58.79	57.68	56.08	5.18	8.04	5.16	NLD	17.69	36.12	45.73	54.19	1.57	2.31	1.25
FJI	31.29	43.97	45.78	47.59	4.92	8.07	4.91	CAN	38.86	70.63	82.67	90.04	1.24	2.48	1.24
JAM	44.68	55.81	57.12	58.60	4.32	6.84	4.33	NZL	41.20	71.03	76.83	80.09	1.17	1.80	1.46
NIC	17.15	21.43	21.56	21.76	4.24	7.47	4.25	KOR	3.28	7.48	11.08	14.60	1.08	1.69	1.11
BLZ	29.53	41.51	42.47	44.12	4.13	6.55	4.12	PRT	12.80	36.75	68.05	88.41	1.00	1.55	1.01
NPL	11.01	13.25	13.57	14.15	3.51	9.09	3.50	ESP	20.68	40.20	45.71	50.53	0.99	1.58	0.98
COM	17.07	18.27	17.61	17.72	3.47	6.17	3.47	DEU	23.32	40.76	48.18	55.19	0.93	1.43	0.88
LBR	16.14	18.85	19.43	20.21	3.44	6.03	3.44	JPN	3.53	8.08	10.64	12.69	0.90	1.42	0.90
DOM	19.90	29.56	30.34	31.46	3.01	4.71	3.01	AUT	27.02	36.37	42.89	50.93	0.88	1.46	0.88
PHL	10.86	18.18	20.65	22.82	2.84	4.75	2.84	GRC	21.96	34.86	36.75	39.25	0.87	1.35	0.86
HND	16.56	24.62	26.35	28.15	2.76	4.34	2.77	FRA	23.66	40.30	53.50	67.48	0.82	1.32	0.81
GMB	11.20	15.43	18.52	21.99	2.72	4.50	2.72	AUS	45.55	66.79	75.61	82.05	0.79	1.25	0.78
CUB	17.42	25.61	25.70	26.01	2.70	4.23	2.70	FIN	8.27	11.10	15.21	20.94	0.77	1.21	0.77

GTM	14.31	20.76	21.22	21.76	2.35	3.69	2.36	ISR	51.74	64.92	72.73	79.99	0.62	0.89	0.59
ECU	13.24	19.35	19.11	19.05	2.35	3.78	2.35	GBR	24.55	51.47	69.63	83.30	0.49	0.81	0.49
TLS	9.60	11.42	12.29	13.36	2.34	4.32	2.34	HUN	7.21	10.50	11.66	13.24	0.42	0.65	0.42
COG	9.75	14.69	16.00	16.56	2.16	3.65	2.17	SVN	19.72	21.46	20.26	19.38	0.39	0.71	0.39
PRY	14.16	15.86	15.59	15.25	2.16	3.69	2.16	CZE	5.13	7.71	8.97	10.70	0.35	0.58	0.36
PAN	7.18	9.51	9.59	9.58	1.93	3.22	1.87	NOR	20.99	30.67	39.63	50.16	0.29	0.54	0.30
GNQ	22.34	25.32	26.22	26.71	1.91	3.20	1.91	IRL	28.82	47.77	57.00	66.88	0.21	0.56	0.18
LAO	17.32	26.75	29.62	31.68	1.90	3.01	1.90	CHL	2.67	4.06	4.53	5.03	0.15	0.24	0.15
RUS	9.84	11.36	11.06	10.62	1.81	2.86	1.82	POL	1.42	1.46	1.65	2.08	0.07	0.11	0.07
WSM	30.65	45.03	43.42	43.61	1.81	2.71	1.84	TUR	2.30	1.57	1.32	1.24	0.03	0.04	0.03
TJK	16.06	18.90	19.25	19.65	1.79	3.05	1.79	MEX	0.83	0.75	0.82	0.90	0.02	0.04	0.02
HTI	19.40	35.56	40.13	43.46	1.79	2.78	1.75	SWE	27.67	40.12	51.94	62.14	-0.00	0.07	-0.01
LKA	12.47	11.41	11.35	11.79	1.63	2.82	1.63	LUX	70.63	87.13	93.43	97.03	-0.06	-0.06	-0.05
TON	56.77	61.51	59.02	58.79	1.57	2.33	1.52	SVK	4.75	5.31	5.63	6.35	-0.10	-0.10	-0.10
MYS	11.16	18.94	21.78	24.87	1.51	2.50	1.51	CHE	43.86	65.97	75.79	84.51	-0.46	-0.45	-0.45
YEM	10.80	15.22	15.62	16.07	1.45	2.38	1.48	EST	30.27	49.68	62.55	73.59	-0.98	-1.39	-0.98

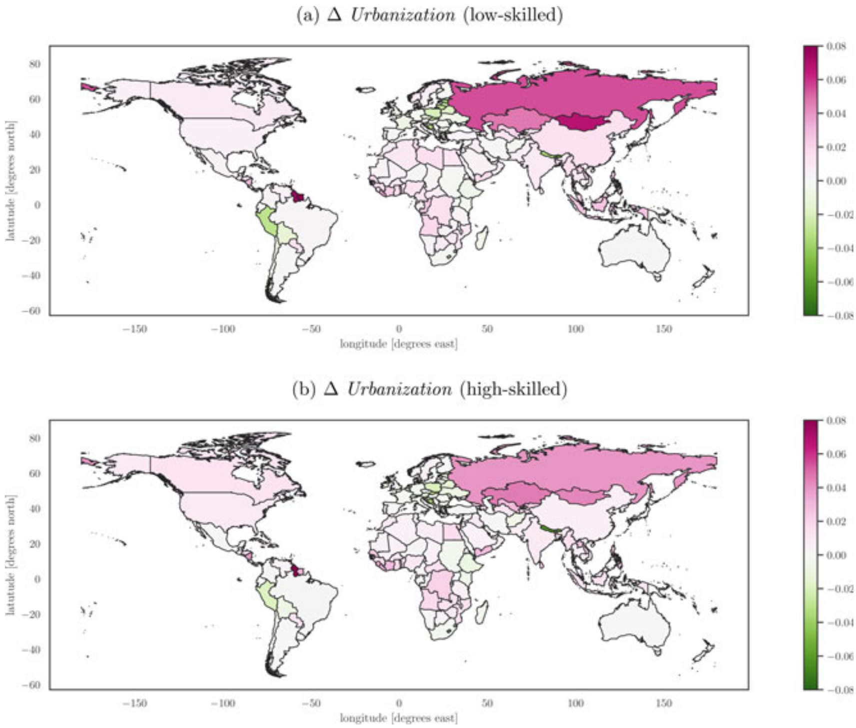

Figure 4. Urbanization due to climate change.
Notes: Figure 4 depicts the percentage point changes in the proportion of urban population that is due to climate change (*RCP 4.5*). It distinguishes between low-skilled and high-skilled populations. Δ*Urbanization* ≙ *Urban share (2100, RCP 4.5) – Urban Share(2100, No CLC)*.

of people involved is relatively small. By contrast, the right-hand panel lists the 30 countries exhibiting the largest climate-related variations in immigration rates by the end of the century. These include OECD countries. It should be noted that the immigration rates reported for the year 2010 are roughly twice as large as those reported in official statistics. The reason for this is that our immigration rates are computed as a proportion of the population aged 25–65 years, rather than as a proportion of the total population. As immigrants mostly belong to this age group, their proportion within the working-age population is much higher than in the total population.

Under constant migration policies and without climate change (i.e., in the *No CLC* scenario), the proportion of immigrants in the total population increases by a factor between 2 and 3 in most OECD countries. These variations are induced by population growth differentials between South and North countries, as well as by the progress in education in the South. Climate change contributes only a little to the rise in migration pressures to the North. In most European countries, the *RCP-4.5* scenario increases the proportion of foreigners by 1–2 percentage points, whereas socio-demographic imbalances increase it by 20–30 percentage points. In the United States, climate change increases the immigration rate by 2.4 percentage points, against 30 percentage points for socio-demographic imbalances. Compared with the

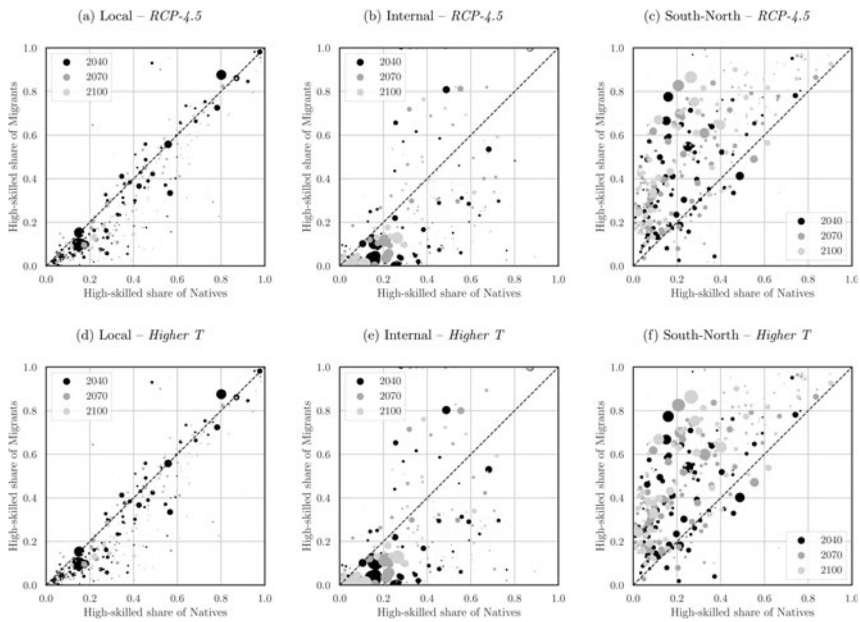

Figure 5. Self-selection in climate migration.

Notes: Figure 5 compares the proportion of college graduates among climate migrants (*Y*-axes) and natives (*X*-axes). It distinguishes between three categories of migrants (local, internal, and South–North) and two climate scenarios [*RCP-4.5* in (a)–(c), and *Higher T* in (d)–(f)]. Bubble sizes are proportional to the square root of the number of movers.

RCP-4.5 scenario, the effect of climate migration is 1.5 times greater in the *Higher T* scenario.

4.3 Effect on urbanization

Turning to internal migration, climate change prompts people to relocate from lower-productivity rural regions to higher-productivity urban regions. Table 1 shows that under the *RCP-4.5* and *Higher SL* scenarios, climate change increases the proportion of the world population living in urban areas by 1 percentage point over the twenty-first century. On average, the largest responses are observed in East Asia and the Pacific, and in Middle East and Northern African countries. Under the *Higher T* scenario, the urbanization responses are 1.5 times greater in all regions. Although these changes may seem small, Figure 4 shows that they mask marked differences between countries and between skill groups. A slight decrease in the urban share is observed in Western European (OECD) countries. By contrast, the urban share increases more rapidly in far north countries and in most countries close to the equator. On average, changes in urban shares are more pronounced among low-skilled workers.

Table A1 in the Appendix lists the 30 countries exhibiting the largest climate-driven changes in urbanization. The urban share increases by more than 5 percentage points in five countries under *RCP-4.5*, and in 15 countries under *Higher SL*. Small developing states such as Guyana, Surinam, Fiji, Sao Tome and Principe, Jamaica, and the Micronesian islands are among the most affected.

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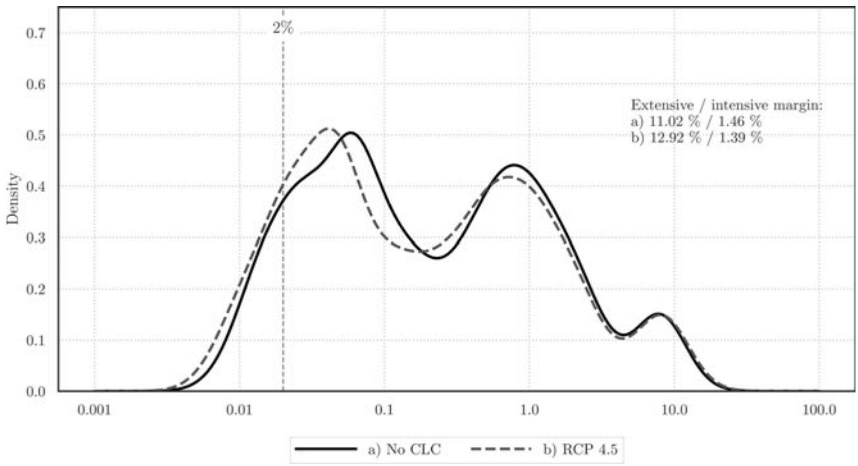

Figure 6. Effect of climate change on income distribution in 2100 (under *RCP-4.5*).
Notes: Figure 6 depicts smoothed predicted distributions of income in 2100 under the *No CLC* (black solid curve), and *RCP-4.5* (gray dashed curve) scenarios. The gray vertical line represents the relative poverty threshold (2% of average income).

4.4 Skill structure of climate migration

We now turn to the self-selection of climate migrants in terms of education level. For each region of origin and for each period, Figure 5 compares the proportions of college graduates among natives (*X*-axis) with the proportions of college graduates among climate emigrants (*Y*-axis). The bubble sizes increase with the number of migrants concerned, while the colors refer to periods. The number of climate migrants is defined as the difference between the number of emigrants in the *RCP-4.5* (top panel) or *Higher T* (bottom panel) scenario, and the number of emigrants in the *No CLC* one. We focus on the three categories of migrants that are strongly impacted by climate change—namely local movers (left-hand panel), rural-to-urban movers (center panel), and S–N migrants (right-hand panel)—and exclude region-wave observations with a negative number of climate migrants. This mostly pertains to rural-to-urban migration in high-income countries, as agricultural productivity increases in countries located above the 35th parallel. Hence, the center panel only includes 140 observations.

Self-selection varies across regions. Nevertheless, whatever the climate scenario, we find that local movers from a majority of regions are slightly less educated than the native population. The process of negative selection is stronger among internal (i.e., rural-to-urban) migrants. Natives born in rural regions of the poor countries are usually poorly educated; those deciding to emigrate within their country are even less educated. By contrast, S–N climate migrants are positively selected along education levels. The proportion of college graduates among S–N migrants exceeds the natives by a factor of 2–3 in most regions. In particular, in relative terms, the intensity of positive selection is large in low-income regions. Hence, high-skilled people from poor regions exhibit a much greater propensity to emigrate to industrialized countries than the less educated when they are confronted with the damage resulting from climate change. The fact that international climate

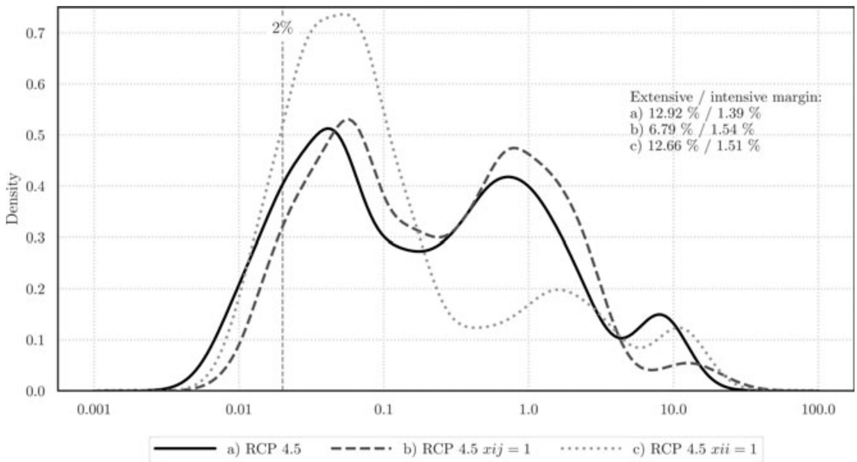

Figure 7. Climate change and inequality without migration (under *RCP-4.5*).
Notes: Figure 7 depicts smoothed predicted distributions of income in 2100 under the *RCP-4.5* climate scenario and alternative migration policies. The gray vertical dashed line represents the relative poverty threshold (2% of average income). The black solid curve gives the inequality responses under current migration costs and policies. The dark gray dashed curve gives the effects obtained after closing all borders. The light gray dotted curve shows the effects obtained after preventing people from migrating between regions/sectors within their country.

migration is of the brain drain type reinforces the adverse impact of climate change in low-income countries.

4.5 Extreme poverty and migration policies

As stated above, climate change makes the world distribution of income more unequal. The income loss is even greater for low-skilled workers trapped in the poorest regions (i.e., rural regions). In our long-term context with sustained TFP growth, we define *Extreme Poverty* in relative terms as the percentage of workers earning <2% of the worldwide average level of income per worker. Figure 6 compares the world distribution of income in 2100 across climate change scenarios. The income level of all types of workers is expressed as percentage of the world average. By considering four groups of workers per country (i.e., two skill groups times two regions) and by ignoring within-group heterogeneity, the density shown in Figure 6 is an approximation of the actual income distribution. The model predicts three peaks by the end of the twenty-first century: one at around 5% of the world average, one slightly below the world average, and one at 10 times the world average. The relative poverty line is represented by the vertical dashed gray line.

Climate change affects the distribution of income below the worldwide average level. We focus here on the extensive margin of poverty, measured by the proportion of the world's population below the relative poverty line, as well as on the intensive margin of poverty. The latter is computed as the mean income of workers in extreme poverty, expressed as percentage of the worldwide average income level. Figure 6 shows that climate change adversely affects extreme poverty. In the *RCP-4.5* scenario, the proportion of the world's population living in extreme poverty increases by 1.9

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percentage points (from 11.0% to 12.9%), and the relative income of the extreme poor decreases by 0.07 percentage points compared with the world average. In the *Higher T* scenario (not shown in Figure 6), the extensive margin increases by 6 percentage points (from 11.0% to 17.0%) and the relative income of the extreme poor decreases by 0.15 percentage points.

It is thus natural to explore whether changes to immigration and urbanization policies could help to limit the effect of climate change on extreme poverty. Predicting mobility responses to a partial or total liberalization of international migration is a complex task [see Delogu *et al.* (2018); Docquier *et al.* (2015)]. Hence, to shed light on the potential effect of future international migration and urban development policies, we compare the *RCP-4.5* scenario with two extreme (and somewhat unrealistic) mobility variants. The first consists of preventing people from migrating internationally from 2040 onwards $\left(x_{b,s,t}^{jr,j'r'} = 1\ \forall j \neq j'\right)$. The resulting income distribution corresponds to the dark gray dashed curve in Figure 7. Our second counterfactual scenario consists of preventing people from migrating between regions within their country from 2040 onwards $\left(x_{b,s,t}^{jr,jr'} = 1\ \forall r \neq r'\right)$, while re-opening the external borders. The resulting income distribution is shown by the light gray dotted curve in Figure 7.

We find that closing the external borders reduces poverty at the extensive margin (6 percentage points) and at the intensive margin. This is due to skill selection in international migration responses to climate change. International migration opportunities mostly benefit high-skilled workers from urban regions. The resulting "brain drain" reduces the low-skilled wage rate in this sector, which slows down urbanization and increases the number of low-skilled workers "trapped" in the rural sector. This implies that relaxing international migration restrictions may exacerbate the poverty responses to climate change. Leaving aside any discussion regarding the political economy of removing migration barriers, as well as the integration issues involved by the skill selectivity of migrants, our simulations suggest that the poverty implications of a climate-related migration policy are highly sensitive to the target group. If the policy affects the poorest individuals from the poorest countries (i.e., low-skilled workers in agriculture), opening borders and issuing new "climatic visas" may be suitable for mitigating the poverty response to climate change in the origin regions. By contrast, if a policy does not affect the self-selection of international migrants or if the screening of potential migrants is imperfect, it is likely to reinforce extreme poverty in the countries of origin.

With regard to internal movements, Figure 7 shows that preventing people from migrating from rural to urban regions has ambiguous effects on extreme poverty. In the poorest regions (where income per capita is below 1% of the world average income), internal migration is a costly option and low-skilled workers are trapped in their region of birth. Preventing the very few high-skilled workers from leaving slightly reduces extreme poverty. In poor regions where income per capita is between 1% and 2% of the world average income, internal migration allows low-skilled people to escape poverty; preventing them from leaving increases extreme poverty. Quantitatively speaking, these two effects balance each other out. It should be noted that preventing internal migration dramatically increases the proportion of the population living on 2–20% of the worldwide average income level, and polarizes the world distribution of income. In line with the Sustainable Development Agenda, our analysis suggests that policies targeting sustainable urban development and smaller internal mobility frictions are key to mitigating the poverty impact of climate change.

5. Conclusion

Climate change is regarded as a significant shock that will substantially change the global economic environment in the coming decades. Indeed, our results strongly support this suggestion. A gradual increase in average temperature levels and the consequent rising sea levels constitute drivers of welfare redistribution across individuals, regions, and countries. Climate change is likely to boost productivity in the rich economies, and strongly harm the poorest countries located close to the equator. Assuming there are no changes to global migration policies, this would induce movements from rural to urban regions and from less-developed to highly-developed countries. The simulations of our model indicate that the overall magnitude of these climate-induced flows reach 70 million (108 million) workers in the *RCP-4.5* (*Higher T*) scenario over the course of the twenty-first century. Interestingly, a significant proportion of these migrants (27% by 2040 and 13% over the whole century) will choose to move locally, and many others (44% by 2040 and 39% over the whole century) will move across regions of their home country. The rest (29% by 2040 and 48% over the whole century) will decide to cross borders. With regard to international migration, we find that S–N migrants constitute an overwhelming part of total flows, while S–S migration is of lesser importance. We predict almost no changes to emigration from North, OECD countries. When looking at the education levels of climate migrants, the model indicates a stark dichotomy of self-selection patterns. While internal movers are predicted to be negatively selected from their home region populations, international migrants are strongly positively selected. The latter indicates that climate change boosts the brain drain from less-developed countries, which, along with an adverse impact on productivity, reinforces divergence in income per capita across the globe.

A significant redistribution of income across regions and countries that widens the inequality gap calls for policy interventions to save people from facing economic losses. Experimenting with migration policies only, we find that closing international borders may reduce aggregate inequality at the cost of individual utility for potential climate emigrants (positively selected) who cannot leave their homeland. By contrast, closing down regional migration significantly adversely affects welfare in the poor regions and accelerates the rise in inequality, as the low-skilled climate migrants become stuck in their region of birth.

As temperatures continue to increase and sea levels rise, the economic prosperity of many millions of people is under threat. Climate change, one of the major challenges for humankind in the next decades, is presumed to induce significant global mobility of people. Our quantitative results not only support this statement, but also give it a slightly different flavor, as the most intensive response is predicted to take place at the local and regional scale. Thus, our results reinforce the call for efficient global policies, but more importantly, highlight the importance of the local and regional context in fighting against the effects of climate change on migration.

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References

Acemoglu, D. (2002) Technical change, inequality, and the labor market. *Journal of Economic Literature* 40(1), 7–72.

Backhaus, A., I. Martinez-Zarzoso and C. Muris (2015) Do climate variations explain bilateral migration? A gravity model analysis. *IZA Journal of Migration* 4(1), 3.

Balk, D., U. Deichmann, G. Yetman, F. Pozzi, S. Hay and A. Nelson (2006). *Determining Global Population Distribution: Methods, Applications and Data* (Vol. 62). Adv Parasitol 62,119–156.

Barrios, S., L. Bertinelli and E. Strobl (2006) Climatic change and rural–urban migration: the case of sub-Saharan Africa. *Journal of Urban Economics* 60(3), 357–371.

Beine, M. and C. Parsons (2015) Climatic factors as determinants of international migration. *The Scandinavian Journal of Economics* 117(2), 723–767.

Berlemann, M. and M. F. Steinhardt (2017) Climate change, natural disasters, and migration—A survey of the empirical evidence. *CESifo Economic Studies* 63(4), 353–385.

Bertoli, S. and J. Fernández-Huertas Moraga (2013) Multilateral resistance to migration. *Journal of Development Economics* 102, 79–100.

Biavaschi, C., M. Burzyński, B. Elsner and J. Machado (2020). Taking the skill bias out of global migration. *Journal of Development Economics*, *forthcoming*, 142C, 102317.

Black, R., N. W. Arnell, W. N. Adger, D. Thomas and A. Geddes (2013) Migration, immobility and displacement outcomes following extreme events. *Environmental Science & Policy* 27, S32–S43.

Black, R., S. R. Bennett, S. M. Thomas and J. R. Beddington (2011) Climate change: migration as adaptation. *Nature* 478(7370), 447.

Boppart, T. (2014) Structural change and the Kaldor facts in a growth model with relative price effects and non-Gorman preferences. *Econometrica* 82(6), 2167–2196.

Burzyński, M., C. Deuster and F. Docquier (2020) Geography of skills and global inequality. *Journal of Development Economics* 142C, 102333.

Burzyński, M., C. Deuster, F. Docquier and J. de Melo (2019) Climate change inequality, and human migration. CEPR Discussion Papers, 13997.

Cai, R., S. Feng, M. Oppenheimer and M. Pytlikova (2016) Climate variability and international migration: the importance of the agricultural linkage. *Journal of Environmental Economics and Management* 79, 135–151.

Cattaneo, C., M. Beine, C. J. Fröhlich, D. Kniveton, I. Martinez-Zarzoso, M. Mastrorillo, K. Millock, E. Piguet and B. Schraven (2019) Human migration in the era of climate change. *Review of Environmental Economics and Policy* 13(2), 189–206.

CIESIN-Columbia University. (2018).

Coniglio, N. D. and G. Pesce (2015) Climate variability and international migration: an empirical analysis. *Environment and Development Economics* 20(4), 434–468.

Dallmann, I. and K. Millock (2017) Climate variability and inter-state migration in India. *CESifo Economic Studies* 63(4), 560–594.

Dao, T., F. Docquier, M. Maurel and P. Schaus (2018) Global migration in the 20th and 21st centuries: the Unstoppable Force of Demography. FERDI Working Paper 223.

Dell, M., B. F. Jones and B. A. Olken (2012) Temperature shocks and economic growth: evidence from the last half century. *American Economic Journal: Macroeconomics* 4(3), 66–95.

Dell, M., B. F. Jones and B. A. Olken (2014) What do we learn from the weather? The new climate-economy literature. *Journal of Economic Literature* 52(3), 740–798.

Delogu, M., F. Docquier and J. Machado (2018) Globalizing labor and the world economy: the role of human capital. *Journal of Economic Growth* 23(2), 223–258.

Desmet, K., D. K. Nagy and E. Rossi-Hansberg (2018) The geography of development. *Journal of Political Economy* 126(3), 903–983.

Desmet, K. and E. Rossi-Hansberg (2015) On the spatial economic impact of global warming. *Journal of Urban Economics* 88, 16–37.

Docquier, F., J. Machado and K. Sekkat (2015) Efficiency gains from liberalizing labor mobility. *Scandinavian Journal of Economics* 117(2), 303–346.

Fiala, N (2015) Economic consequences of forced displacement. *The Journal of Development Studies* 51(10), 1275–1293.

Giorgetta, M., J. Jungclaus, C. Reick, S. Legutke, R. Badedr, M. Bottinger, V. Brovkin, T. Crueger, M. Esch, K. Fieg, K. Glushak, V. Gayler, H. Haak, H. D. Hollweg, T. Ilyina, S. Kinne, L. Kornblueh, D. Matei, T. Mauritsen, U. Mikolajewicz, W. Müller, D. Notz, F. Pithan, T. Raddatz, S. Rast, R. Redler, E. Roeckner, M. Salzmann, H. Schmidt, R. Schnur, J. Segschneider, K. Six, M. Stockhause, C. Timmreck, J. Wegner, H. Widmann, K. H. Wieners, M. Claussen, J. Marotzke and B. Stevens (2013) Climate and carbon cycle changes from 1850 to 2100 in MPI-ESM simulations for the Coupled Model Intercomparison Project phase 5. *Journal of Advances in Modeling Earth Systems* 5(3), 572-597.

Giorgetta, M., J. Jungclaus, C. Reick, S. Legutke, V. Brovkin, T. Crueger, M. Esch, K. Fieg, K. Glushak, V. Gayler, H. Haak, H. D. Hollweg, S. Kinne, L. Kornblueh, D. Matei, T. Mauritsen, M. Thorsten, U. Mikolajewicz, W. Müller, D. Notz, T. Raddatz, S. Rast, E. Roeckner, M. Salzmann, H. Schmidt, R. Schnur, J. Segschneider, K. Six, M. Stockhause, J. Wegner, H. Widmann, K. H. Wieners, M. Claussen, J. Marotzke and B. Stevens (2012) CMIP5 simulations of the Max Planck Institute for Meteorology (MPI-M) based on the MPI-ESM-LR model. WDCC at DKRZ, Max Planck Institute for Meteorology: Hamburg.

Gollin, D., D. Lagakos and M. E. Waugh (2014) The agricultural productivity gap. *The Quarterly Journal of Economics* 129(2), 939–993.

Henderson, J. V., A. Storeygard and U. Deichmann (2017) Has climate change driven urbanization in Africa? *Journal of Development Economics* 124, 60–82.

Ibáñez, A. M. and A. Moya (2006). The impact of intra-state conflict on economic welfare and consumption smoothing: empirical evidence for the displaced population in Colombia. Available at SSRN 1392415.

Kellenberg, D. and A. M. Mobarak (2011) The economics of natural disasters. *Annual Review of Resource Economics* 3(1), 297–312.

Kennan, J. (2013) Open borders. *Review of Economic Dynamics* 16(2), L1–L13.

Klein, P. and G. Ventura (2009) Productivity differences and the dynamic effects of labor movements. *Journal of Monetary Economics* 56(8), 1059–1073.

Kubik, Z. and M. Maurel (2016) Weather shocks, agricultural production and migration: evidence from Tanzania. *The Journal of Development Studies* 52(5), 665–680.

Lucas, R. E. (1988) On the mechanics of economic development. *Journal of Monetary Economics* 22(1), 3–42.

Lucas, R. E. (2009) Trade and the diffusion of the industrial revolution. *American Economic Journal: Macroeconomics* 1(1), 1–25.

Marchiori, L., J.-F. Maystadt and I. Schumacher (2012) The impact of weather anomalies on migration in sub-Saharan Africa. *Journal of Environmental Economics and Management* 63(3), 355–374.

Marchiori, L., J.-F. Maystadt and I. Schumacher (2017) Is environmentally induced income variability a driver of human migration? *Migration and Development* 6(1), 33–59.

McFadden, D. L. (1974) Conditional logit analysis of qualitative choice behavior. In P. Zarembka (ed.), *Frontiers in Econometrics*. New York, NY: Academic Press, pp. 105–142.

Moss, R. H., J. A. Edmonds, K. A. Hibbard, M. R. Manning, S. K. Rose, D. P. van Vuuren, T. R. Carter, S. Emori, M. Kainuma, T. Kram, G. A. Meehl, J. F. B. Mitchell, N. Nakicenovic, K. Riahi, S. J. Smith, R. J. Stouffer, A. M. Thomson, J. P. Weyant and T. J. Wilbanks (2010) The next generation of scenarios for climate change research and assessment. *Nature*, 463(7282), 747–756.

Oppenheimer M., B. C. Glavovic, J. Hinkel, R. van de Wal, A. K. Magnan, A. Abd-Elgawad, R. Cai, M. Cifuentes-Jara, R. M. DeConto, T. Ghosh, J. Hay, F. Isla, B. Marzeion, B. Meyssignac and Z. Sebesvari (2019) Sea level rise and implications for low lying islands, coasts and communities. The Intergovernmental Panel on Climate Change. in: Pörtner, H.-O. et al. (eds), IPCC Special Report on the Ocean and Cryosphere in a Changing Climate, Cambridge University Press, Cambridge, UK.

Ottaviano, G. I. and G. Peri (2012) Rethinking the effect of immigration on wages. *Journal of the European Economic Association* 10(1), 152–197.

Perch-Nielsen, S. L., M. B. Bättig and D. Imboden (2008) Exploring the link between climate change and migration. *Climatic Change* 91(3–4), 375.

Piguet, E., A. Pécoud and P. De Guchteneire (2011) Migration and climate change: an overview. *Refugee Survey Quarterly* 30(3), 1–23.

Restuccia, D. and G. Vandenbroucke (2013) The evolution of education: a macroeconomic analysis. *International Economic Review* 54(3), 915–936.

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Rigaud, K. K., A. de Sherbinin, B. Jones, J. Bergmann, V. Clement, K. Ober, J. Schewe, S. Adamo, B. McCusker, A. Heuser and A. Midgley (2018) *Groundswell: Preparing for Internal Cimate Migration*. Washington, DC: World Bank.

Shayegh, S. (2017) Outward migration may alter population dynamics and income inequality. *Nature Climate Change* 7(11), 828.

Stocker, T. F., D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P. M. Midgley (2014) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of Ipcc the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge: UK and NY.

Stumpf, R. (2012) Distance to nearest coastline: 0.01-degree grid: Land. NASA Goddard Space Flight Center (GSFC) Ocean Color Group. Retrieved 2020-09-30. https://oceancolor.gsfc.nasa.gov/docs/distfromcoast/

Tadono, T., H. Ishida, F. Oda, S. Naito, K. Minakawa and H. Iwamoto (2014) Precise global DEM generation by ALOS PRISM. *ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences*, II-4, 71–76. http://www.isprs-ann-photogramm-remote-sens-spatial-inf-sci.net/II-4/71/2014/ doi: 10.5194/isprsannals-II-4-71-2014

Taylor, K. E., R. J. Stouffer and G. A. Meehl (2012) An overview of CMIP5 and the experiment design. *Bulletin of the American Meteorological Society* 93(4), 485–498.

Vollrath, D. (2009) How important are dual economy effects for aggregate productivity? *Journal of Development Economics* 88(2), 325–334.

Young, A. (2013) Inequality, the urban-rural gap, and migration. *The Quarterly Journal of Economics* 128 (4), 1727–1785.

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Appendix

Table A1. Top 30 changes in urban share due to climate change

Rank	ΔRCP-4.5				ΔHigher T				ΔHigher SL			
	ISO	HS	ISO	LS	ISO	HS	ISO	LS	ISO	HS	ISO	LS
1	GUY	10.30	SUR	8.75	GUY	16.79	GUY	16.40	GUY	10.15	SUR	9.01
2	STP	6.71	GUY	7.46	SLB	13.07	SUR	15.12	STP	6.71	GUY	7.30
3	FJI	5.69	MNG	6.81	STP	12.81	STP	13.91	FJI	5.67	MNG	6.99
4	SLB	5.62	STP	6.32	FJI	10.08	MNG	11.77	SLB	5.59	STP	6.32
5	JAM	4.80	RUS	5.44	FSM	9.00	RUS	10.18	KAZ	5.16	RUS	5.41
6	KAZ	4.57	KAZ	4.70	JAM	8.13	SLV	9.37	JAM	4.93	KAZ	5.25
7	FSM	4.52	SLV	4.67	NIC	7.58	SLB	9.25	MNG	4.48	SLV	4.86
8	MNG	4.37	WSM	4.01	MNG	7.53	LBR	7.31	FSM	4.31	PAN	4.59
9	RUS	3.96	LBR	3.84	TLS	7.15	KAZ	7.30	RUS	3.95	WSM	3.88
10	NIC	3.90	SLB	3.78	RUS	7.06	FJI	7.09	NIC	3.90	LBR	3.84
11	TLS	3.82	FJI	3.77	KAZ	7.04	PAN	6.50	TLS	3.82	FJI	3.76
12	SLE	3.41	PAN	3.59	COM	6.01	WSM	6.26	BLZ	3.43	SLB	3.75
13	BLZ	3.39	JAM	3.09	LBR	5.96	NIC	5.97	SLE	3.41	JAM	3.19
14	WSM	3.24	NIC	3.00	SLE	5.70	TLS	5.63	SUR	3.24	NIC	3.00
15	LBR	3.24	TLS	2.87	BLZ	5.38	JAM	5.52	LBR	3.24	TLS	2.87
16	SUR	3.16	IDN	2.59	WSM	5.27	IDN	4.45	WSM	3.14	GMB	2.60

(*Continued*)

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Table A1. (*Continued.*)

Rank	*ΔRCP-4.5*				*ΔHigher T*				*ΔHigher SL*			
	ISO	HS	ISO	LS	ISO	HS	ISO	LS	ISO	HS	ISO	LS
17	COM	3.11	GMB	2.58	SUR	5.12	GMB	4.40	COM	3.11	IDN	2.58
18	UZB	2.96	COG	2.35	CIV	4.94	PHL	4.27	YEM	3.06	COG	2.36
19	YEM	2.93	PHL	2.26	YEM	4.82	FSM	4.26	UZB	2.98	PHL	2.25
20	CIV	2.84	CIV	2.20	VUT	4.75	COG	4.07	CIV	2.84	CIV	2.20
21	PHL	2.64	LAO	2.11	PHL	4.72	VUT	3.81	PHL	2.63	LAO	2.11
22	VUT	2.50	GNB	2.10	UZB	4.65	CIV	3.79	VUT	2.50	GNB	2.10
23	LAO	2.45	MYS	2.08	LAO	4.02	GNQ	3.51	LAO	2.46	BGD	2.07
24	SEN	2.39	MDV	2.07	SEN	3.97	MYS	3.50	SEN	2.38	MYS	2.07
25	GNQ	2.25	FSM	2.07	LKA	3.94	GNB	3.48	GNQ	2.25	MDV	2.07
26	KGZ	2.22	GNQ	2.00	GNQ	3.87	LAO	3.46	KGZ	2.25	GNQ	2.00
27	TON	2.21	UZB	1.97	TGO	3.60	MDV	3.40	LKA	2.20	UZB	1.99
28	LKA	2.20	VUT	1.96	COD	3.52	AGO	3.36	TGO	2.14	BLZ	1.97
20	TGO	2.14	SEN	1.94	KGZ	3.50	SEN	3.33	COD	2.10	VUT	1.95
30	COD	2.10	TGO	1.92	TON	3.47	TGO	3.33	TON	2.03	FSM	1.95

Notes: Table A1 depicts the percentage point changes in the proportions of the urban population due to climate change. It distinguishes between low-skilled and high-skilled populations and three climate scenarios (*RCP 4.5*, *Higher T*, and *Higher SL*). For example, *ΔRCP 4.5* = *Urban share(2100, RCP 4.5)* – *Urban Share(2100, No CLC)*. Country codes are provided in Table A2.

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Table A2. Countries included in our model and their ISO codes

Country	Code	Country	Code	Country	Code	Country	Code
Afghanistan	AFG	Denmark	DNK	Lesotho	LSO	Saint Lucia	LCA
Albania	ALB	Djibouti	DJI	Liberia	LBR	Saint Vincent and Grenadines	VCT
Algeria	DZA	Dominican Rep.	DOM	Libya	LBY	Samoa	WSM
Angola	AGO	Ecuador	ECU	Lithuania	LTU	Sao Tome and Principe	STP
Argentina	ARG	Egypt	EGY	Luxembourg	LUX	Saudi Arabia	SAU
Armenia	ARM	El Salvador	SLV	Macedonia	MKD	Senegal	SEN
Australia	AUS	Equatorial Guinea	GNQ	Madagascar	MDG	Serbia	SRB
Austria	AUT	Eritrea	ERI	Malawi	MWI	Sierra Leone	SLE
Azerbaijan	AZE	Estonia	EST	Malaysia	MYS	Singapore	SGP
Bahamas	BHS	Ethiopia	ETH	Maldives	MDV	Slovakia	SVK
Bahrain	BHR	Fiji	FJI	Mali	MLI	Slovenia	SVN
Bangladesh	BGD	Finland	FIN	Malta	MLT	Solomon Islands	SLB
Barbados	BRB	France	FRA	Mauritania	MRT	South Africa	ZAF
Belarus	BLR	Gabon	GAB	Mauritius	MUS	Spain	ESP
Belgium	BEL	Gambia	GMB	Mexico	MEX	Sri Lanka	LKA
Belize	BLZ	Georgia	GEO	Micronesia	FSM	Sudan	SDN
Benin	BEN	Germany	DEU	Mongolia	MNG	Suriname	SUR
Bhutan	BTN	Ghana	GHA	Montenegro	MNE	Swaziland	SWZ
Bolivia	BOL	Greece	GRC	Morocco	MAR	Sweden	SWE
Bosnia and Herzegovina	BIH	Grenada	GRD	Mozambique	MOZ	Switzerland	CHE

(*Continued*)

Table A2. (*Continued.*)

Country	Code	Country	Code	Country	Code	Country	Code
Botswana	BWA	Guatemala	GTM	Myanmar	MMR	Syria	SYR
Brazil	BRA	Guinea	GIN	Namibia	NAM	Tajikistan	TJK
Brunei Darussalam	BRN	Guinea-Bissau	GNB	Nepal	NPL	Tanzania	TZA
Bulgaria	BGR	Guyana	GUY	Netherlands	NLD	Thailand	THA
Burkina Faso	BFA	Haiti	HTI	New Zealand	NZL	Timor-Leste	TLS
Burundi	BDI	Honduras	HND	Nicaragua	NIC	Togo	TGO
Cambodia	KHM	Hungary	HUN	Niger	NER	Tonga	TON
Cameroon	CMR	Iceland	ISL	Nigeria	NGA	Trinidad and Tobago	TTO
Canada	CAN	India	IND	Norway	NOR	Tunisia	TUN
Cape Verde	CPV	Indonesia	IDN	Oman	OMN	Turkey	TUR
Central African Rep.	CAF	Iran	IRN	Pakistan	PAK	Turkmenistan	TKM
Chad	TCD	Iraq	IRQ	Palestine	PSE	Uganda	UGA
Chile	CHL	Ireland	IRL	Panama	PAN	Ukraine	UKR
China	CHN	Israel	ISR	Papua New Guinea	PNG	United Arab Emirates	ARE
China, Hong Kong	HKG	Italy	ITA	Paraguay	PRY	United Kingdom	GBR
Colombia	COL	Jamaica	JAM	Peru	PER	United States	USA
Comoros	COM	Japan	JPN	Philippines	PHL	Uruguay	URY
Congo	COG	Jordan	JOR	Poland	POL	Uzbekistan	UZB
Congo DR	COD	Kazakhstan	KAZ	Portugal	PRT	Vanuatu	VUT
Costa Rica	CRI	Kenya	KEN	Qatar	QAT	Venezuela	VEN
Croatia	HRV	Kuwait	KWT	Republic of Korea	KOR	Vietnam	VNM

Cuba	CUB	Kyrgyzstan	KGZ	Republic of Moldova	MDA	Yemen	YEM
Cyprus	CYP	Laos	LAO	Romania	ROU	Zambia	ZMB
Czech Republic	CZE	Latvia	LVA	Russia	RUS	Zimbabwe	ZWE
Côte d’Ivoire	CIV	Lebanon	LBN	Rwanda	RWA		