Climate change, Inequality and Migration

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Abstract

This paper investigates the long-term effects of climate change on labor migration at various spatial scales (local, interregional and international). We build a two-sector, two-class, intertemporal model of the world economy. For each country, we endogenize the effect of rising temperature and sea levels on population and productivity growth, education decisions, income inequality, extreme poverty and mobility decisions. Climate change creates conditions that are conducive to increasing urbanization and international migration from developing to rich countries. In our median scenario (+2.09°C, +1.1m), we predict that climate change induces voluntary and forcibly displacements of about 120 million adult workers in the course of the 21st century. Nevertheless, under current migration laws and policies, most of these workers will move short distances, and only 19% of them will opt for long-haul migration to OECD destinations. Climate change has limited effects on international emigration and immigration rates, even when considering more extreme scenarios. Larger amounts of internal and international migrations can be obtained when adding direct utility losses and conflicts over resources, two effects that are more uncertain and harder to quantify.

1 Introduction

There is strong evidence that the global mean surface temperature of the world has increased since the beginning of the 19th century, and that the process has accelerated since 1980. Temperatures are expected to increase by 1 to 3°C over the 21st century, and recent
studies suggest that, once adding an increment from storm surge, the sea level is expected to rise by 1 to 2 metres by 2050 (e.g., Rigaud et al., 2018). Global warming and sea level rise are two major ingredients of long-term climate change (henceforth CLC), which will alter ecosystems and affect several economic outcomes such as productivity, health, drudgery of work, conflicts, and more (see Dell et al., 2014). Damages will vary across space because the economic effects of temperature are nonlinear (i.e., initial temperature matters) and countries are heterogeneously exposed to sea-level rise. Low-latitude countries that have contributed the least to CLC will be the most adversely affected. Hence, migratory pressures, both internal and international, will presumably be strongest in poor countries and are sometimes portrayed as a first-order adaptation mechanism to CLC. The scant evidence from past episodes suggests, however, that the scale and type of mobility responses are uncertain and context-specific.

This paper studies the long-term effects of CLC on migration. For the first time, we use the state-of-the-art tools of the migration literature to model the long-term mobility responses to CLC at various spatial scales, and their interactions with global inequality and extreme poverty over the 21st century. The existing literature has mostly looked at the short-term impacts of fast-onset variables (e.g., weather anomalies, storms, hurricanes, torrential rains, floods, landslides, etc.), as opposed to long-run CLC or slow-onset variables (e.g., temperature trends, desertification, rising sea level, coastal erosion, etc.).\(^1\) Long-run extrapolation of these estimates is questionable,\(^2\) and there is very little theoretical modelling of the population and economic consequences of CLC. Contrary to existing studies, our forward-looking, general equilibrium model covers the world economy and accounts for the economic and sociodemographic contexts in which mobility decisions are made. We model migration decisions as the outcome of a micro-founded, random utility model, and jointly account for the main migration mechanisms mentioned in the literature. Increases in temperature affect income and incentives to migrate (as in Desmet and Rossi-Hansberg, 2015, or Shayegh, 2017), and the rising sea level forces people and activities to move (as in Rigaud et al., 2018). In more extreme scenarios, we also consider that CLC may cause direct utility costs (linked to health or to the drudgery of work) and conflicts over resources. In addition, our migration technology is parameterized to match international and urbanization data of the last 30 years.\(^3\) In our framework, geography matters: each one of 179 countries is populated by two types of agents (college graduates and the less educated) living in two regions (agriculture and non-agriculture) and heterogeneously affected by sea level rise (flooded and unflooded areas). The model also endogenizes the productivity, fertility, and education responses to CLC which, together with skill-specific migration decisions, govern the evolution of human capital and income inequality. Such a unified model is helpful for quantifying the long-run demographic and economic responses to CLC and their sensitivity.

We contribute to the growing literature on the linkages between CLC and migration. As explained above, existing studies are mostly empirical and focused on responses to

\(^1\) Note that in the long-run, there is a correlation between the slow-onset indicators and the frequency of fast-onset shocks.

\(^2\) Although it has been documented that the 2°C rise in temperatures during the Medieval warm period between the 9th and 14th centuries resulted in large relocation of people and economic activity (Fagan, 2008), the world has changed and it is difficult to draw causal inference about long-run effects from the past 30 years because global warming has been modest and migration restrictions have gradually increased.

\(^3\) Using backcast exercises, Dao et al. (2018) demonstrate that such a model fits the past international migration trends very well.
extreme weather shocks. Recent reviews of the literature are provided in Perch-Nielsen et al. (2008), Piguet et al. (2011), Millock (2015), Berlemann and Steinhardt (2017) or Cattaneo et al. (2018). The meta-analysis in Beine and Jeusette (2018) reveals a diversity in methodological choices in empirical studies. They identify four important methodological choices, namely (i) the measurement of the dependent variable, (ii) the decision to include or exclude indirect effects of CLC, (iii) the analytical specification of the transmission technology, and (iv) the identification strategy. Methodological diversity is reflected in the heterogeneity of findings. While CLC has consistently emerged as a potent driver of internal migration (Piguet et al., 2011; Barrios et al., 2006; Kubik and Maurel, 2016; Dallmann and Millock, 2013; Henderson et al., 2017), its effect on international migration is not consensual. Some studies find important international migration outflows that are directly associated to weather shocks (Coniglio and Pesce, 2015; Backhaus et al., 2015; Cai et al., 2016) or indirectly induced by CLC-driven pressures on income in urban areas (Marchiori et al., 2012, 2015; Beine and Parsons, 2015). Others attempt to explain why migration responses are small, and even why migration does not respond or responds negatively to climate shocks (Black et al., 2011; Black et al., 2013; Cattaneo et al., 2018). Overall, using empirical approaches to predict the migration responses to global warming poses three major problems. Firstly, difficulties in identifying a clear-cut effect are due to the fact that climate variables closely interact with the other economic and political drivers of migration. Secondly, mobility decisions are context-specific and can be influenced by a large number of factors that vary across regions and countries (such as the country size, the level of economic development, the political context or some cultural characteristics). Thirdly, the effects of CLC have not yet fully materialized.

In light of these limitations, we propose an alternative, micro-founded approach that includes a spatial dimension. Our study is part of an incipient literature pioneered by Desmet and Rossi-Hansberg (2015) (henceforth DRH) who investigate the economic costs of CLC by modelling the interaction of mobility and production changes in the continuous space. Unlike DRH, we assume that each economy is composed of two regions, agriculture

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4Earlier studies show that millions of people will be forcibly displaced in the future as a result of climate change (Gemenne, 2011; Piguet et al., 2011). In response to the diversity of findings across studies, the paradigm has gradually changed with recent studies seeing migration as an adaptation strategy among several others (not the least costly one).

5Some studies focus on international migration (to all countries or to selected destinations) while others tackle internal migration and urbanization (Henderson et al., 2017)

6An indirect link is identified when climate variables affect mobility decisions through other variables such as changes in productivity and income (Marchiori et al., 2012; Beine and Parsons, 2015), or conflicts over resources (Miguel et al., 2004; Gleditsch, 2012).

7The literature distinguishes between monotonic or unconditional specifications (i.e., models capturing responses that are independent of the context), and conditional specifications that allow the eventual outcome to depend on socioeconomic and political characteristics of the individuals, households or regions exposed to climatic events.

8Cattaneo and Peri (2016) report that a gradual increase in the level of temperature reduces migration outflows from poor countries due to the presence of financial constraints. Bazzi (2017) finds similar results on Indonesia, as well as Findley (1994) on Mali. On the contrary, Jayachandran (2006), Gray and Mueller (2012), Mueller et al. (2014) find that landless households respond more than the wealthy ones in India, Pakistan and Bangladesh, respectively.

9In DRH all equilibria are spatially symmetric with prices and factor allocations identical for all locations at a given latitude. Desmet, Nagy and Rossi-Hansberg (2018) model the mobility of people and the dynamics of income inequality at a more detailed spatial scale (1x1 degree cells across the globe), but disregard CLC.
and nonagriculture, to accommodate empirical estimates that show consistently that the impact of CLC on productivity will be greater in agriculture than in manufacturing. We are looking for first-order effects of CLC on people and countries in a framework that takes into account that the (endogenous) geography of skills affects migration decisions through differences in incentives, fertility decisions, and migration costs. Another related study is Shayegh (2017), which models the effect of CLC on fertility rates, income inequality and human capital accumulation in developing countries. He assumes the probability to emigrate is skill-specific and increasing in temperature without microfoundations. As to the effects of CLC, DRH and Shayegh (2017) model the effect of the change in temperature on productivity. We also account for sea-level rise – about which scientific consensus is strong – which affects countries differentially, and we implement additional mechanisms of transmission such as direct utility losses and conflicts. The emphasis on migratory mechanisms comes at a cost. In our model, unlike the macro models of Nordhaus (2000) and DRH, CO2 emissions are exogenously subsumed in the simulation scenario rather than as a result of mitigation decisions included in the model. There are two reasons for this. Firstly, the effects of population change on the concentration of greenhouse gas and global mean temperature are highly uncertain. As discussed in the next section, projections of mean air temperature levels strongly vary across models for a given emissions scenario. Secondly, Shayegh (2017) shows that endogenizing the CLC response to migration has negligible impact on the overall results given the small number of migrants compared to the whole population. We assume that CLC and its directs impacts are exogenous to the economies under investigation.

Our simulations reveal that CLC induces small positive effects on the worldwide average level of income per worker but makes the world distribution of income more unequal. Workers employed in countries located between the 35th parallel suffer income losses, particularly those employed in agriculture. CLC also increases world extreme poverty at both extensive and intensive margins. Coupled with the fact that the rising sea level induces forced displacements, CLC creates conditions that are conducive to increasing urbanization and international migration. Our Intermediate CLC scenario assumes +2.09°C and a 1.1m rise in the sea level. It accounts for climate-driven productivity losses and forced displacements. Compared to a constant climate scenario, the worldwide number of working-age movers increases by 120 million in the course of the 21st century. Compared to Rigaud et al. (2018), we find similar levels of climate migration but offer additional insight on the type of migration. In particular, when considering forced displacements and productivity effects, we find that far more climate migrants will move within their own countries than across borders: 66% of movers relocate within their region and 15% migrate from rural areas to cities. Hence, only 19% opt for long-haul migration to an OECD destination country. CLC increases the world proportion of international migrants by 0.2 percentage points in the long-run. This only corresponds to 1/20 of the no-CLC worldwide migration rate, and to 1/5 of the gradual increase predicted for the 21st century. The latter trend is mostly driven by demographic imbalances between developing and rich countries, and by the education trends. These effects increase less than proportionately if the rise in temperature is twice as large (i.e., +4°C in the 21st century): the number of movers reaches 185 millions, including 27% of long-haul migrants. In addition, a relaxation of immigration restrictions for migrants originating from the countries incurring the largest CLC-driven income losses has limited effects on extreme poverty headcounts and on poverty depth. Our results for international migration are highly robust to the scale of the sea level rise. This is due to the fact that forcibly displaced people essentially move
locally. However, two major sources of uncertainty surround our projections. Our numerical experiments reveal that conflicts over resources could become a key determinant of climatic migration pressures, and that direct utility losses due to CLC have potentially important effects on internal and international migration.

The rest of this paper is organized as follows. Section 2 illustrates the heterogeneous implications that CLC induces for the world economy. Section 3 describes our two-sector, two-class model and explains its parameterization. Section 4 presents our results. Finally, Section 5 concludes.

2 Heterogeneous effects of CLC

In this section, we show that low-latitude countries in general, and their rural regions in particular, will be the most adversely affected by CLC. This implies that CLC creates conditions that are conducive to increasing urbanization and international migration from developing to rich countries. In Section 2.1, we define three moderate climate scenarios that combine future variations in global temperature and sea level. Then, Section 2.2 discusses two direct transmission channels—changes in total factor productivity and forced displacements—through which CLC affects the world economy and the migration decisions of people. These channels will be accounted for in the overlapping generations model described in Section 3. Note that more extreme climate scenarios and two additional channels of transmission—direct utility losses and conflicts, which are more uncertain and more difficult to quantify—will be considered in Section 4.2.

2.1 Moderate climate scenarios

Most analysts predict that CLC will lead to a gradual rise in the mean surface-temperature and in the sea level over the 21st century. Uncertainty about CLC, about damages, and about the interaction between CLC and damages is large. To take this into account, we define three moderate scenarios referred to as:

- **CLC-Minimalist.** This scenario involves $+0.09^\circ C$ in temperature and $+0m$ in sea level over the 21st century.
- **CLC-Intermediate.** Involving $+2.09^\circ C$ in temperature and $+1.1m$ in sea level.
- **CLC-Maximalist.** Involving $+4.09^\circ C$ in temperature and $+1.3m$ in sea level.

We consider these changes as exogenous in our model. We thus disregard the endogeneity of CLC, which involves uncertain links between CLC, economic activity and CO2 emissions. The scenario selection is discussed below.

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10Stern (2013) reports that since an increase of $+3^\circ C$ (likely to occur when concentrations increase from the current 400ppm to 750ppm) has not been experienced for around 3 million years, we are in uncharted territory when it comes to modeling these likely effects. He lists the effects that might emerge strongly at $+3^\circ C$. Schelling (2007) remarked about the climate sensitivity parameter ($S$) which defines the equilibrium surface warming from a doubling of the stock of CO2 emissions that "for a quarter of a century, the range of uncertainty [about $S$] has been a factor of 3". This uncertainty comes out clearly in the range of damage changes produced by the same warming scenario in the different climate models reviewed by Burke et al. (2015).
Projections of temperature. – We follow three steps to construct our projections of temperature levels. In a first step, we collect raw data on monthly temperature levels and projections from the Climate Change Knowledge Portal (CCKP) of the World Bank Group. Our variable of interest is the near-surface monthly mean air temperature level. Figure 1a illustrates the cross-country relationship between mean surface-temperature and latitude in 2010. Bubble sizes are proportional to the working-age population in each of the 179 countries included in the model. Temperature levels are negatively correlated with latitude.

As for temperature projections, they are organized in 20-year climatological windows for the years 2020-2039, 2040-2059, 2060-2079, and 2080-2099. The CCKP projections are obtained from the Coupled Model Intercomparison Project Phase 5 (CMIP5) distribution (Taylor et al., 2012) which distinguishes between several scenarios for the Representative Concentration Pathways (RCP) (Moss et al., 2010). The median-emission scenario is called RCP-4.5. In addition, for each RCP, the CCKP provides data for 16 models obtained from different research institutes. When these models are ranked by ascending order of the yearly temperature anomaly for the fourth 20-year climatological window of 2080-2099, the medium-resolution model of the Institut Pierre Simon Laplace (the ipsl_cm5a_mr variant) takes the 8th (median) position in RCP-4.5. We select this ipsl_cm5a_mr variant as our Intermediate scenario.

This Intermediate scenario predicts that the temperature levels increase gradually in all countries, and that the mean surface temperature of the world will increase by 2.09°C over the 21st century. Figure 1b plots the 2010-2100 variation in the average of our monthly levels of temperature by degree of latitude for the 179 countries. For most countries this difference takes a positive value between 0°C and 4°C. Overall, the correlation between latitude and the predicted temperature change is small. Hence, most countries will experience an increase in temperature, and all country types (small and large, rich and poor) will be affected with a similar intensity.

In the Minimalist scenario, we start from the Intermediate and uniformly decrease the temperature by 2°C in all countries, which basically shifts the estimated curve downwards by 2°C in Figure 1b. Hence, this scenario predicts that the mean surface-temperature will increase by 0.09°C over the 21st century, virtually implying the absence of global warming. The Minimalist scenario roughly corresponds to the most optimistic variant under RCP-2.6. Similarly, the Maximalist scenario uniformly increases the temperature by 2°C in all countries, which shifts the estimated curve upwards by 2°C. Hence, it predicts that the mean surface-temperature will increase by 4.09°C. The Maximalist scenario roughly corresponds to the median variant under RCP-8.5.

Sea level rise (SLR). – Potentially, the second most serious impact of long-term CLC is the rise in the sea level. According to IPCC (2014), millions of individuals living at an altitude of less than one meter will be affected during the 21st century. Predicting changes in sea level is difficult, because the dynamics of ocean heat uptake and ice sheets/glaciers are poorly understood. Still, Vermeer and Rahmstorf (2009) developed a methodology that links global SLR (on time scales of decades to centuries) to global mean temperature.

\[11\] Figure 1b depicts the temperature difference for values between -2°C and +10°C. Three outliers are not depicted: Russia and Canada include large territories in the northern hemisphere and exhibit high negative differences, Nepal has high levels of altitude and exhibits very large positive differences.

\[12\] In Appendix A.1, we discuss how raw temperature levels are adjusted to account for within-country disparities in temperature and population density, and how climate windows are linked to the time periods of our overlapping generations model.
Notes: Latitude (geographic coordinate) is measured on the X-axis and bubble sizes are proportional to the population aged 25-64 in the year 2010.

They estimate the SLR for each global temperature scenario of the IPCC involving a global temperature change above 2°C. The estimated relationship between the sea-level variation (SLR) and the global change in the mean surface-temperature (ΔT) is concave if SLR is forced to be equal to zero for ΔT = 0, and almost linear if SLR(0) is not specified.\footnote{It is very well proxied using a log-linear function: $SLR = 0.89 + 0.3\ln(\Delta T)$; the R-squared of this regression equals 0.985. The shape of the function and the proxied observations are depicted in Figure A1b in the Appendix.}

In the Intermediate temperature scenario (+2.09°C), this curve implies that the sea level is expected to rise by 1.1 m. Given the gradual change in temperature in our baseline scenario, the sea level is predicted to rise by 0.78 m in 2040, by 0.99 m in 2070 and by 1.1 m in 2100. In another study, DeConto and Pollard (2016) model the impact of Antarctic ice cap on overall SLR. In their reference estimation, they find changes which closely correspond to our projections: under the RCP-4.5 scenario, they predict a mean elevation of 1.05 m and a confidence interval of ±0.30 m, which is very similar to our Intermediate scenario.

In the Minimalist scenario, we assume a constant sea level. Remember this scenario also involves a constant mean surface temperature. Although it can be considered as unrealistic and extreme, we use it as a no-CLC point of reference. In particular, the difference between the Intermediate and the Minimalist scenario gives valuable information about the mean expected effects of CLC.

In the Maximalist scenario, the mean surface temperature increases by 4.09°C. Using the estimated relationship of Vermeer and Rahmstorf (2009), this involves a 1.3 m SLR by 2100 (0.97 m in 2040 and 1.18 m in 2070). More extreme scenarios will be considered in Section 4.2.

Figure 1: Intermediate CLC scenario (2010-2100)
2.2 Damage functions

The “damage function” is central to estimating the potential economic implications of global temperature and sea-level variations. Two channels of transmission are systematically accounted for in our simulations. Firstly, we allow changes in temperature to affect the level of TFP in agriculture and in nonagriculture. Secondly, SLR induces forced displacement of people. This leads to substantial costs as flooded areas are usually the most densely populated areas in a region. More extreme scenarios involving direct utility losses and conflicts over resources will be considered later. Figure 2 illustrates the heterogeneous TFP responses to CLC, which are treated as exogenous shocks in our model. Figure 3 shows the country-specific shares of population living under 1.1m and between 1.1 and 1.3m as of the year 2010. Although these shares differ from the long-run (endogenous) population shares which will be impacted in the course of the 21st century, they give an indication of the scale of forced displacements induced by SLR.

Temperature and productivity. To model the effect of temperature, we follow DRH who estimate an inverted-U shaped relationship between temperature \((T)\) and total factor productivity in agriculture and in the manufacturing sector. They include a quadratic scale factor \(G_r(T)\) in the TFP of sector \(r\) that depends on the level of temperature. It can be expressed as:

\[
G_r(T) = \max \left\{ g_{0r} + g_{1r} T + g_{2r} T^2; 0 \right\}
\]

where \((g_{0r}, g_{1r}, g_{2r})\) is a triplet of sector-specific parameters, and \(r = (a, n)\) denotes agriculture \((a)\) and nonagriculture \((n)\). If \(g_{1r} > 0\) and \(g_{2r} < 0\), the ideal temperature in sector \(r\) is given by \(T^*_r = -\frac{g_{1r}}{2g_{2r}}\). The level of TFP increases with temperature in regions with average temperature below \(T^*_r\); it decreases with temperature in warmer regions.

Agronomic studies have been used to calibrate the quadratic relationship between TFP and temperature in agriculture (Mendelsohn et al., 1994; Le, 2010; Lobell and Burke, 2010). To account for the possibility of adapting to climate change by switching between crops, DRH estimate the envelope of the quadratic relationships obtained for different crops. This gives \((g_{0a}, g_{1a}, g_{2a}) = (-2.24, 0.308, -0.0073)\), which implies an optimal temperature \(T^*_a\) of 21.1°C. It also implies that agricultural yields are nil when temperature \(T_a\) is below 9.4°C or greater than 32.9°C. Figure 2a shows the relationship between temperature and agricultural productivity, after normalizing the maximal level of productivity to unity and smoothing \(G_a(T)\) using a Gaussian function to avoid zero-productivity levels.

To estimate the quadratic relationship in the nonagricultural sector, DRH use data on population density (a proxy for economic development) by latitude. They consider 1,000 bands of 9.6km each, and estimate the relationship between (smoothed) levels of population density and temperature. They obtain \((g_{0n}, g_{1n}, g_{2n}) = (0.3, 0.08, -0.0023)\), which gives an optimal temperature \(T^*_n\) of 17.4°C. The quadratic is compatible with the

\[14\text{In unreported results, we also accounted for the potential productivity losses due to the rising sea level. We used the NASA database and estimate of the fraction of land that could be flooded. Using population and land data, we compared the density of people in flood-risk areas and in the rest of the region and assume, in line with Desmet and Rossi-Hansberg (2015), that disparities in population density reflect disparities in total factor productivity. For each country, we produced region-specific estimates of the productivity loss caused by the sea-level rise. These productivity losses are small (in countries with access to the sea, we obtained an average loss of 1.2% in rural regions and of 0.7% in rural regions), either because the share of population located in flooded areas is small, or because productivity differences are small. For this reasons, this mechanism is not included in the model.}

\[15\text{On average, low elevation coastal zones (situated at an altitude of less than ten meters) account for 2.2% of dry land and 10.5% of the world population (see McGranahan et al., 2007).} \]
findings of Dell and Jones (2014) who show that, on average, industrial output decreases by 2% for a 1°C increase in temperature; it is also compatible with specialization and trade patterns by level of latitude. Although the curve is flatter than in agriculture, nonagricultural productivity is nil when temperature \( T_n \) is below -3°C or greater than 38°C. Figure 2b shows the relationship between temperature and nonagricultural productivity, after normalizing the maximal level of productivity to unity and smoothing \( G_n(T) \) using a Gaussian function to avoid zero-productivity levels. For each country and period, we plug the monthly population-weighted levels of temperature in the period \( t, T_{m,t} \), in \( G_a(.) \) and \( G_n(.) \). We then compute the averages of these TFP levels for each period \( t \):

\[
G_{r,t} = \frac{1}{12} \sum_{m=1}^{12} G_r(T_{m,t}).
\]

Remember that expected variations in temperature are poorly correlated with latitude (see Figure 1b). Nevertheless, the current level of temperature is highly correlated with latitude (see Figure 1a): countries above the 35th parallel have average temperature levels under 20°C, while countries at lower latitude have a higher average temperature. Hence, the very same variation in temperature will induce dramatically different effects on productivity. Figure 2c and 2d compare the predicted percentage variation in productivity implied by the Maximalist (with respect to the Intermediate) with those implied by the Intermediate scenario (with respect to the Minimalist). Both graphs include the 3-order polynomial trend. These pairwise comparisons allow visualizing the effect of a 2°C increase in temperature on productivity starting from different initial temperature levels. Figure 2c depicts the effect of the variations in temperature on agricultural productivity. Compared to the Minimalist (no CLC) scenario, the Intermediate (+2.09°C) induces a productivity loss of 20% in countries close to the equator, and a gain of 25% at high latitudes. And compared to the Intermediate, the Maximalist scenario (another +2°C) results in slightly greater losses. Figure 2d focuses on non-agricultural productivity. Compared to the Minimalist scenario, the Intermediate (+2°C) induces a productivity loss of 10-15% in countries close to the equator, and a gain of 5% for countries at high latitudes. Compared to the Intermediate, the Maximalist scenario results in similar damages.

**SLR and forced displacements.** – To proxy the number of people affected by SLR, we need to determine the fraction of the population living in low-lying coastal areas. We use the NASA database on the distribution of the population by elevation, by country and by region type (urban versus rural). We assume rural regions are totally specialized in agriculture and urban regions only produce nonagricultural goods. For each country, we produce region-specific estimates of the fraction of population living under 1.1m using a 4-parameter interpolation of the NASA data. The world map in Figure 3a illustrates the resulting percentage of the population by country in the year 2010 living in low-lying areas. About 70 million people aged 25 to 64 were living under 1.1m in that year. They will be close to 80 million in 2040. On the map, countries are grouped into ten bins, each bin corresponding to a population share living in low-lying areas. In a few countries the percentage of population living below 1.1m is larger than 10%. This is the case for less than 7.3% of the countries. For less than 19% of the countries the percentage value is larger than 5%.

Overall, the map shows that the more affected countries are not necessarily the poorest. SLR mostly affect countries with a large share of population located along the coasts of all seas and oceans, or in the major river deltas and estuaries. The percentage value equals
Notes: On Figures 2c and 2d, latitude (geographic coordinate) is measured on the X-axis and bubble sizes are proportional to the population aged 25-64 in the year 2010. We measure deviations as (Intermediate-Minimalist)/Minimalist and (Maximalist-Intermediate)/Intermediate.

89.1% in the Netherlands. This share 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. This indicates that both rich and poor countries would be adversely affected by a SLR. It would certainly be an exaggeration to consider that these roughly 80 million individuals will all migrate internationally in the near future. Some of them will move to another region or country. Others will relocate within the same region or invest to build sea defences (especially in high-income countries).

Finally, Figure 3b depicts the share of the population living between 1.1 and 1.3m of elevation in 2010. As in Figure 3a, countries are grouped by the size of their share into ten groups. Overall, the population share is small. The share is smaller than 10% in all countries, and exceeds 5% only in a handful of countries. The largest share is obtained in the Netherlands, with a value equal to 8%.
Figure 3: Forced displacements in the moderate scenarios

Notes: Own calculations based on NASA population data.

3 Model

We construct an overlapping generations model of the world economy that depicts a set of countries and regions populated by two period-lived agents (children and adults). One period is meant to represent the active life of one generation (30 years) and we ignore the retirement period for simplicity. There are two types of adults at each period, with \( s = (h, l) \) denoting college-educated workers (\( h \)) and the less educated (\( l \)). In virtually all countries, college graduates are more migratory than the less educated.

Our framework is similar to Delogu et al. (2018) but relies on different technological assumptions, and includes two sectors/regions with heterogeneous productivity, with \( r = (a, n) \) denoting agriculture (\( a \)) and nonagriculture (\( n \)), in each country. For simplicity, we assume that firms in both sectors produce the same good. Contrary to DRH or Shayegh (2017), we thus disregard variations in the relative price of the agricultural good, and we normalize the price of the single good to unity. In theory, change in relative price can mitigate or reinforce the effect of CLC. DRH show that CLC has uncertain effects on the relative price because it induces a rise in agricultural productivity in the North
and a decline in the South. In addition, Burzynski et al. (2018) show that responses to productivity and migration policy reforms are quantitatively similar when considering that agricultural and nonagricultural goods are identical or imperfect substitutes as in Boppart (2014).

Compared to Burzynski et al. (2018), our model formalizes the link between CLC and the productivity gap between regions. We add another source of heterogeneity. Each region consists of two areas of time-varying size, with \( b = (f,d) \) denoting the flooded area \( (f) \) and the unflooded/dry area \( (d) \). The model endogenizes the levels of productivity of both sectors/regions as a function of the level of temperature, of rising sea level, and of the average level of schooling of the resident workers. There is no economic activity and no one can live in the flooded area.

Adults are the only decision makers. They maximize their well-being and decide where to live, how much to consume, and how much to invest in the quantity and quality of their children. As far as the location decision is concerned, each new adult decides whether to stay in the region where she grew up (if the area of birth does not get flooded), to move locally within the same region (if the area of birth gets flooded), to emigrate to the other region within the same country, or to emigrate abroad. This choice depends on economic disparities between regions and countries, on moving costs, on the area type, as well as on the direct effect of temperature on utility. Fertility and education decisions are governed by a warm-glow motive. Adults directly value the quality and quantity of children. It follows that the dynamic structure of the model is totally recursive. In this section, we describe our technological and preference assumptions, we derive the profit- and utility-maximization conditions, and we define the world-economy intertemporal equilibrium.

### 3.1 Technology

Production is only feasible in the unflooded area of each region \( r \). We assume that output is proportional to labor in efficiency units. Each country is characterized by a pair of CES (constant elasticity of substitution) production functions with two types of labor (as in Gollin et al., 2014, or Vollrath, 2009). The output level in region \( r \) at time \( t \) is given by:

\[
Y_{r,t} = A_{r,t} \left( \sum_s \eta_{r,s,t} \ell_{r,s,t}^{\sigma_r-1} \right)^{\frac{1}{\sigma_r-1}} \forall t, r, \tag{1}
\]

where \( A_{r,t} \) denotes the productivity scale factor in sector \( r \) at time \( t \) (referred to as TFP henceforth), \( \eta_{r,s,t} \) is a sector-specific variable governing the relative productivity of workers of type \( s \) (such that \( \eta_{r,h,t} + \eta_{r,l,t} = 1 \)), and \( \sigma_r \) is the sector-specific elasticity of substitution between the two types of worker. The number of adult workers of type \( s \) employed in region \( r \) at time \( t \) is denoted by \( \ell_{r,s,t} \), which differs from the total population, \( L_{r,s,t} \) (as explained below).

---

16 Considering goods as heterogeneous in a small open economy context, variations in the relative price of the agricultural good can mitigate or reinforce the urbanization process. It mitigates it if CLC decreases the share of agriculture in the world total output (i.e., if the output loss in low-latitude countries exceeds the output gain in the North). In the benchmark scenario of DRH (Figure 4), changes in relative price are small. If the relative price of agricultural goods increases, the migration responsiveness predicted by our model can be considered as an upper-bound.

17 Such a model without physical capital features a globalized economy with a common international interest rate. This hypothesis is in line with Kennan (2013) or Klein and Ventura (2009) who assume that capital “chases” labor.
Wage rates are determined by the marginal productivity of labor and there is no involuntary unemployment. This yields:

\[
    w_{r,s',t} = A_{r,t} \left( \sum_s \eta_{r,s,t} \ell_{r,s,t} \right) \frac{1}{\sigma_r-1} \eta_{r,s',t} \ell_{r,s',t} \quad \forall s', t, r.
\]

(2)

It follows that the wage ratio between high-skilled and low-skilled workers in region \( r \) is given by:

\[
    \Gamma^w_{r,t} = \frac{w_{r,h,t}}{w_{r,l,t}} = \Gamma^\eta_{r,t} \left( \Gamma^\ell_{r,t} \right)^{1-\sigma_r} \quad \forall t, r,
\]

(3)

where \( \Gamma^\ell_{r,t} \equiv \frac{\ell_{r,h,t}}{\ell_{r,l,t}} \) is the skill ratio in the labor force of region \( r \) at time \( t \), and \( \Gamma^\eta_{r,t} \equiv \frac{\eta_{r,h,t}}{\eta_{r,l,t}} \) measures the skill bias in relative productivity.

Two types of technological externality are factored in. First, we assume that the TFP level in each sector depends on the level of temperature and on the average level of schooling of workers. We have:

\[
    A_{r,t} = \gamma_t \bar{A}_r G(T_{r,t}) Z(\Gamma^\ell_{r,t}) \quad \forall t, r,
\]

(4)

where \( \gamma_t \) is a time trend in productivity which is common to all countries (\( \gamma > 1 \)), \( \bar{A}_r \) is the exogenous component of TFP in region \( r \) (reflecting exogenous factors such as the proportion of arable land, soil fertility, land ruggedness, etc.), \( G(T_{r,t}) \) is the inverted-U shaped function of temperature described in Section 2.2, and \( Z(\Gamma^\ell_{r,t}) \) a simple Lucas-type aggregate externality (see Lucas 1988) capturing the fact that college-educated workers facilitate innovation and the adoption of advanced technologies. We assume \( Z(\Gamma^\ell_{r,t}) = (\Gamma^\ell_{r,t})^{\epsilon_r} \) is a concave function of the skill-ratio in the resident labor force, where \( \epsilon_r \in (0,1) \) is the sector-specific elasticity of TFP to the skill-ratio in sector \( r \).

Second, we assume a directed, skill-biased technical change. As the technology improves, the relative productivity of college-educated workers increases, and this is particularly the case in the nonagricultural sector (Acemoglu, 2002; Restuccia and Vandenbroucke, 2013). For example, Autor et al. (2003) show that computerization is associated with declining relative industry demand for routine manual and cognitive tasks, and increased relative demand for nonroutine cognitive tasks. The observed relative demand shift favors college versus non-college labor. We write:

\[
    \Gamma^\eta_{r,t} = \bar{\Gamma}^\eta_r \left( \Gamma^\ell_{r,t} \right)^{\kappa_r} \quad \forall t, r,
\]

(5)

where \( \bar{\Gamma}^\eta_r \) 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 \( r \).

### 3.2 Preferences

The number of new native adults of type \( s \) at time \( t \) is denoted by \( N_{r,s,t} \). Depending on the elevation structure of the region and on the sea-level rise, part of the region may be flooded at the beginning of the period. If so, a fraction \( \Theta_{r,t} \) of the native population is forced to leave. We denote the number of forcibly displaced people by \( N^f_{r,s,t} = \Theta_{r,t} N_{r,s,t} \), and the rest of the native population as \( N^d_{r,s,t} = (1-\Theta_{r,t}) N_{r,s,t} \). Only the latter may decide not to move. New adults make consumption, fertility, education and migration decisions in early adult life. As illustrated on Figure 4, those who grew up in the unflooded area of the region have the choice between staying in the region (at no cost), emigrating to
another region $r'$ within the same country (requiring an effort $x_{r'r}$), or emigrating to an OECD country (requiring an effort $x_{rF}$). Individuals who grew up in the flooded area have the possibility to relocate in the same region (from the flooded to the unflooded area). They lose their residential capital and incur a monetary cost that corresponds to a fraction $B$ of their lifetime income. They can also emigrate to another region or to another country at the same cost as those who grew up in the unflooded area.

![Figure 4: Movement decisions](image)

### 3.2.1 Individuals raised in unflooded areas

We first focus on individuals who grew up in the unflooded area ($d$) of their region of birth. Individual decisions to emigrate result from the comparison of discrete alternatives, staying in the region of birth, emigrating to the other region, or to a foreign country. To model these decisions, we use a logarithmic outer utility function with a deterministic and a random component. The utility of an adult of type $s$, born in the unflooded area of region $r^*$, moving to the unflooded area of region/country $r$ is given by:

$$U^{d}_{r^*,r,s,t} = \ln v^{d}_{r,s,t} + \ln(1 - x^{r^*,r,s,t}) + \xi^{d}_{r^*,r,s,t} \quad \forall s, t, r^*, r$$  

(6)

where $v^{d}_{r,s,t} \in \mathbb{R}$ is the deterministic level of utility that can be reached in the location $r$ at period $t$ (governed by the inner utility function described below), $x^{r^*,r,s,t} \leq 1$ captures the effort required to migrate from region $r^*$ to location $r$ (such that $x^{r^*,r^*,s,t} = 0$). Migration costs are exogenous; they vary across location pairs, across education levels, and over time. The individual-specific random taste shock for moving from country $r^*$ to $r$ is denoted by $\xi^{d}_{r^*,r,s,t} \in \mathbb{R}$ and follows an iid Type-I Extreme Value distribution with a common scale parameter $\mu > 0$ (this scale parameter governs the responsiveness of migration decisions to changes in $v^{d}_{r,s,t}$ and $x^{r^*,r,s,t}$). Although $\xi^{d}_{r^*,r,s,t}$ is individual-specific, we omit individual subscripts for notational convenience.

In line with Galor and Weil (2000), Galor (2011), de la Croix and Doepke (2003, 2004), the inner utility $\ln v^{d}_{r,s,t}$ is a function of the climate conditions in region $r$ at time $t$ ($T_{r,t}$),\(^{18}\) consumption ($c^{d}_{r,s,t}$), fertility ($n^{d}_{r,s,t}$) and the probability that each child becomes highly skilled ($p^{d}_{r,s,t}$):

\(^{18}\)E.g., effect of temperature on health, drudgery of work, etc.
\[
\ln v^d_{r,s,t} = \ln(1 - \tau_{r,t}) + \ln \rho^d_{r,s,t} + \theta \ln \left(n^d_{r,s,t} + \rho^d_{r,s,t}\right) \quad \forall s, t, r, \tag{7}
\]

where \(\theta \in (0, 1)\) is a preference parameter for the quantity and quality of children, and \(\tau_{r,t}\) is a possible utility loss directly caused by CLC (see Section 4.2).

The probability that a child becomes high-skilled increases with the share of time that is spent in education (\(q^d_{r,s,t}\)):

\[
\pi_r + \rho^d_{r,s,t} \lambda \quad \forall s, t, r, \tag{8}
\]

where \(\pi_r\) is an exogenous parameter that is region-specific and \(\lambda\) governs the elasticity of knowledge acquisition to education investment.

A type-\(s\) adult in region \(r\) receives a wage rate \(w_{r,s,t}\) per unit of time worked. Raising a child requires a time cost \(\phi\) (thereby reducing the labor market participation rate), and each unit of time spent by a child in education incurs a cost equal to \(E_{r,t}\). The budget constraint writes as:

\[
c^d_{r,s,t} = w_{r,s,t}(1 - \phi n^d_{r,s,t}) - n^d_{r,s,t} q^d_{r,s,t} E_{r,t}. \tag{9}
\]

It follows that the labor supply of each type-\(s\) adult in region \(r\) at time \(t\) is given by:

\[
\ell^d_{r,s,t} = 1 - \phi n^d_{r,s,t}. \tag{10}
\]

In the following sub-sections, we solve the optimization problem backward. We first determine the optimal fertility rate and investment in education in a given location \(r\), which characterizes the optimal level of utility, \(v^d_{r,s,t}\), that can be reached in any location. We then characterize the choice of the optimal location.

**Education and fertility.** – Each adult in region \(r\) maximizes her utility (7) subject to the constraints (8) and (9). Solving the system of first-order conditions for an interior solution gives:

\[
\begin{align*}
q^d_{r,s,t} &= \frac{\lambda \phi w_{r,s,t} - \pi_r E_{r,t}}{(1 - \lambda) E_{r,t}} \quad \forall s, t, r, \\
n^d_{r,s,t} &= \frac{w_{r,s,t}}{\phi w_{r,s,t} - \pi_r E_{r,t}} \quad \forall s, t, r.
\end{align*} \tag{11}
\]

The cost of education is assumed to be proportional to the wage of high-skilled workers in the region, multiplied by a fixed, region-specific factor \(\psi_{r,t}\) (capturing education policy/quality, population density, average distance to schools, etc.):

\[
E_{r,t} = \psi_{r,t} w_{r,h,t} \quad \forall r, s. \tag{12}
\]

The deterministic indirect utility function can be obtained by substituting the first-order conditions into (7). This yields:

\[
\begin{align*}
\ln \nu_{r,h,t}^d &= \chi_r + \ln \left(w_{r,h,t}\right) - \theta \lambda \ln \left(\psi_{r,t}\right) - \theta \ln \left(\frac{\phi - \pi_r \psi_{r,t}}{\psi_{r,t}}\right) \\
\ln \nu_{r,l,t}^d &= \chi_r + \ln \left(w_{r,l,t}\right) - \theta \lambda \ln \left(\psi_{r,t}\right) - \theta \ln \left(\frac{\phi - \pi_r \psi_{r,t} \Gamma^w_{r,t}}{\phi - \pi_r \psi_{r,t} \Gamma^w_{r,t}}\right) \\
&\quad + \ln \left(\frac{\phi(1 + \theta \lambda)(1 - \Gamma^w_{r,t}) - \pi_r \psi_{r,t} \Gamma^w_{r,t}(1 + \theta(1 - \Gamma^w_{r,t}))}{\phi - \pi_r \psi_{r,t} \Gamma^w_{r,t}}\right)
\end{align*} \tag{13}
\]

where \(\chi_r = \ln(1 - \tau_{r,t}) + \theta \ln \left(\frac{\theta}{1 + \theta}(1 - \lambda)^{1 - \lambda} \lambda \right) - \ln(1 + \theta)\) include the direct effect of CLC on utility (\(\tau_{r,t}\)).

**Migration.** – Given their taste characteristics (captured by \(\xi\)), each individual chooses the location that maximizes her/his utility, defined in Equation (6). Under the Type I
Extreme Value distribution with scale \( \mu \) for \( \xi \), McFadden (1974) shows that the emigration rate from region \( r^* \) to a particular destination \( r \) is governed by a logit expression. The emigration rate is given by:

\[
\frac{M_{r^*r,s,t}^d}{N_{r^*r,s,t}^d} = \frac{\exp \left( \frac{\ln v_{r^*r,s,t}^d + \ln (1-x_{r^*r,s,t})}{\mu} \right)}{\sum_k \exp \left( \frac{\ln v_{r^*r,s,t}^d + \ln (1-x_{r^*k,s,t})}{\mu} \right)} = \frac{(v_{r^*r,s,t})^{1/\mu}(1-x_{r^*r,s,t})^{1/\mu}}{\sum_k (v_{r^*k,s,t})^{1/\mu}(1-x_{r^*k,s,t})^{1/\mu}}.
\]

Skill-specific emigration rates are endogenous and comprised between 0 and 1. Individuals that grew up in region \( n \) (resp. \( a \)) have the choice between staying in their region of origin \( n \) (resp. \( a \)), moving to the other region \( a \) (resp. \( n \)), or emigrating to a foreign country \( F \). The emigration rates from \( r^* \) to a particular destination \( r \) depend on the utility levels attainable in all regions \( k \) of the world. The choice to emigrate internally or internationally are thus interdependent.

Staying rates \( (M_{r^*r,s,t}^d/N_{r^*r,s,t}^d) \) are governed by the same logit model. It follows that the emigrant-to-stayer ratio \( (m_{r^*r,s,t}) \) is governed by the following expression:

\[
m_{r^*r,s,t} = \frac{M_{r^*r,s,t}^d}{M_{r^*r,s,t}^d} = \frac{(v_{r^*r,s,t})^{1/\mu}(1-x_{r^*r,s,t})^{1/\mu}}{\sum_k (v_{r^*k,s,t})^{1/\mu}(1-x_{r^*k,s,t})^{1/\mu}}.
\]

Equation (14) is a gravity-like migration equation, which states that the ratio of emigrants from region \( r^* \) to location \( r \) to stayers in region \( r^* \) (i.e., individuals born in \( r^* \) who remain in \( r^* \)), is an increasing function of the utility achievable in the destination location \( r \) and a decreasing function of the utility attainable in \( r^* \). The proportion of migrants from \( r^* \) to \( r \) also decreases with the bilateral migration cost \( x_{r^*r,s,t} \). Labor is not perfectly mobile across sectors/regions; internal migration costs \( (x_{an,s,t}) \) and \( (x_{na,s,t}) \) capture private costs and the legal/visa costs imposed by the destination countries. Similarly, international migration costs \( (x_{aF,s,t}) \) and \( (x_{nF,s,t}) \) capture private costs and the legal/visa costs imposed by the destination countries. They are also assumed to be exogenous.

Heterogeneity in migration tastes implies that emigrants select all destinations for which \( x_{r^*r,s,t} < 1 \) (if \( x_{r^*r,s,t}=1 \), the corridor is empty).

### 3.2.2 Forcibly displaced people

Individuals raised in the flooded area of region \( r^* \) (denoted by the superscript \( f \)) are forced to move. If they relocate into the unflooded area of their region of birth \( r^* \), they face a relocation cost equivalent to a fraction \( B \) of their lifetime income. Hence, their budget constraints write as:

\[
c_{r^*s,t}^f = (1-B)w_{r^*s,t}(1-\phi n_{r^*s,t}^q) - n_{r^*s,t}^q q_{r^*s,t}^q E_{r,t}.
\]

This relocation cost affects their fertility rate \( (n_{r^*s,t}^q) \), investment in education \( (q_{r^*s,t}^q) \) and consumption level \( (c_{r^*s,t}^q) \). Their labor supply is given by \( \ell_{r^*s,t}^q = 1-\phi n_{r^*s,t}^q \). Hence, the utility of staying in the region becomes:

\[
\begin{align*}
\ln v_{r^*s,t}^q = \chi_{r^*s,t} + \ln (w_{r^*s,t}^q) + \ln (1-B) - \theta \lambda \ln (\psi_{r^*s,t}) - \theta (1-\lambda) \ln \left( \phi - \pi_{r^*s} \psi_{r^*s,t} \right) \\
\ln v_{r^*s,t}^q = \chi_{r^*s,t} + \ln (w_{r^*s,t}^q) + \ln (1-B) - \theta \lambda \ln (\psi_{r^*s,t}) - \theta (1-\lambda) \ln \left( \phi - \pi_{r^*s} \psi_{r^*s,t} \frac{\Gamma_{r^*s,t}}{\Gamma_{r^*s,t}^w} \right) \\
+ \ln \left( \frac{\phi + \theta \lambda (1-B) / \Gamma_{r^*s,t}^w - \pi_{r^*s} \psi_{r^*s,t} (1+\theta \lambda (1-B) / \Gamma_{r^*s,t}^w) \Gamma_{r^*s,t}^w (1-B) / \Gamma_{r^*s,t}^w}{\phi - \pi_{r^*s} \psi_{r^*s,t} \Gamma_{r^*s,t}^w (1-B)} \right) .
\end{align*}
\]
It follows that the emigrant-to-stayer ratio \( m_{r,s,t}^{I} \) for forcibly displaced people is governed by:

\[
m_{r,s,t}^{I} = \frac{M_{r,s,t}^{I}}{M_{r,s,t}^{I}} = \left( \frac{v_{r,s,t}^{d}}{v_{r,s,t}^{d}} \right)^{1/\mu} (1 - x_{r,s,t})^{1/\mu}
\]

Since \( v_{r,s,t}^{d} < v_{r,s,t}^{d} \), forcibly displaced people tend to migrate more than those who grew up in unflooded regions.

### 3.3 Dynamics and intertemporal equilibrium

We can characterize the equilibrium structure of the resident population in the unflooded area of the region \( \forall s, t, r \):

\[
\begin{align*}
L_{n,s,t} &= \frac{N_{n,s,t}^{d}}{1+m_{n,s,t}+m_{a,f,s,t}} + \frac{N_{n,s,t}^{d}}{1+m_{n,s,t}+m_{a,f,s,t}} + \frac{m_{a,n,s,t}N_{n,s,t}^{d}}{1+m_{a,n,s,t}+m_{a,f,s,t}} + \frac{m_{a,n,s,t}N_{n,s,t}^{d}}{1+m_{a,n,s,t}+m_{a,f,s,t}} \\
L_{a,s,t} &= \frac{N_{n,s,t}^{d}}{1+m_{n,s,t}+m_{a,f,s,t}} + \frac{N_{n,s,t}^{d}}{1+m_{n,s,t}+m_{a,f,s,t}} + \frac{m_{a,n,s,t}N_{n,s,t}^{d}}{1+m_{a,n,s,t}+m_{a,f,s,t}} + \frac{m_{a,n,s,t}N_{n,s,t}^{d}}{1+m_{a,n,s,t}+m_{a,f,s,t}}.
\end{align*}
\]

The total labor supply is given by:

\[
\begin{align*}
L_{n,s,t} &= \frac{N_{n,s,t}^{d}}{1+m_{n,s,t}+m_{a,f,s,t}} + \frac{N_{n,s,t}^{d}}{1+m_{n,s,t}+m_{a,f,s,t}} + \frac{m_{a,n,s,t}N_{n,s,t}^{d}}{1+m_{a,n,s,t}+m_{a,f,s,t}} + \frac{m_{a,n,s,t}N_{n,s,t}^{d}}{1+m_{a,n,s,t}+m_{a,f,s,t}} \\
L_{a,s,t} &= \frac{N_{a,s,t}^{d}}{1+m_{a,n,s,t}+m_{a,f,s,t}} + \frac{N_{a,s,t}^{d}}{1+m_{a,n,s,t}+m_{a,f,s,t}} + \frac{m_{a,n,s,t}N_{a,s,t}^{d}}{1+m_{a,n,s,t}+m_{a,f,s,t}} + \frac{m_{a,n,s,t}N_{a,s,t}^{d}}{1+m_{a,n,s,t}+m_{a,f,s,t}}.
\end{align*}
\]

Together with the number and structure of the resident population at time \( t \), fertility and education decisions \( (n_{r,s,t}^{b}, p_{r,s,t}^{b}, q_{r,s,t}^{b}) \) of predetermined variables, the size and structure of the labor supply \( (N_{r,s,t+1} \forall r, s, t) \) at time \( t + 1 \). For all \( t, r \), we have:

\[
\begin{align*}
N_{n,h,t+1} &= \sum_{s} \frac{N_{n,s,t}^{d}m_{n,s,t}p_{n,s,t}^{b}}{1+m_{n,s,t}+m_{a,f,s,t}} + \frac{N_{n,s,t}^{d}m_{n,s,t}p_{n,s,t}^{b}}{1+m_{n,s,t}+m_{a,f,s,t}} + \frac{m_{a,n,s,t}N_{n,s,t}^{d}m_{a,n,s,t}p_{n,s,t}^{b}}{1+m_{a,n,s,t}+m_{a,f,s,t}} + \frac{m_{a,n,s,t}N_{n,s,t}^{d}m_{a,n,s,t}p_{n,s,t}^{b}}{1+m_{a,n,s,t}+m_{a,f,s,t}} \\
N_{a,h,t+1} &= \sum_{s} \frac{N_{a,s,t}^{d}m_{a,s,t}p_{a,s,t}^{b}}{1+m_{a,s,t}+m_{a,f,s,t}} + \frac{N_{a,s,t}^{d}m_{a,s,t}p_{a,s,t}^{b}}{1+m_{a,s,t}+m_{a,f,s,t}} + \frac{m_{a,n,s,t}N_{a,s,t}^{d}m_{a,n,s,t}p_{a,s,t}^{b}}{1+m_{a,n,s,t}+m_{a,f,s,t}} + \frac{m_{a,n,s,t}N_{a,s,t}^{d}m_{a,n,s,t}p_{a,s,t}^{b}}{1+m_{a,n,s,t}+m_{a,f,s,t}}.
\end{align*}
\]

Similar expressions characterize the evolution of the low-skilled population, except that \( p_{r,s,t}^{b} \) must be replaced by \((1 - p_{r,s,t}^{b})\) on the numerator of each term. An intertemporal equilibrium for the world economy can be defined as following:

**Definition 1** For a set \( \gamma, \theta, \lambda, \phi, \mu, B \) of common parameters, a set \( \{\sigma_{r}, \epsilon_{r}, \kappa_{r}\} \) of sector-specific elasticities, a set \( \{\Gamma_{r,t}, \Gamma_{r,t}^{d}, \Gamma_{r,t}^{s}, \Gamma_{r,t}^{p}, \Gamma_{r,t}^{q}, \Gamma_{r,t}^{n}, \Gamma_{r,t}^{a}, \Gamma_{r,t}^{b}, N_{r,s,0}\} \) of predetermined variables, an intertemporal equilibrium is a set \( \{A_{r,t}, E_{r,t}, \bar{w}_{r,s,t}, w_{r,s,t}, \bar{v}_{r,s,t}, \bar{v}_{r,s,t}, E_{r,t}, m_{r,s,t}, \bar{N}_{r,s,t+1}, L_{r,s,t}, \bar{r}_{r,s,t}\} \) of endogenous variables, which simultaneously satisfies technological constraints (4), (5) and (12), profit maximization conditions (2), utility maximization conditions (11), (13) and (14) in all countries and regions of the world, and such that the equilibrium structure and dynamics of population satisfy (15), (16) and (17).

---

19In the OECD member states, these variables should be supplemented by the the inflow of immigrants, \( I_{r,s,t} \). For simplicity, we assume that the distribution of immigrants by destination is time-invariant, calibrated on the year 2010. Equation (14) also determines the outflow of international migrants by education level.
The equilibrium level of the other variables described above (in particular, $\Gamma_{r,t}$, $\Gamma_{r,t}^\eta$, $\Gamma_{r,t}^w$ as well as urbanization rates and international migration outflows and inflows) can be computed as a by-product of the reduced set of endogenous variables. Note that equilibrium wage rates are obtained by substituting the labor force variables into the wage equation (2), thereby assuming full employment. By the Walras law, the market for goods is automatically balanced.

3.4 Parameterization

In this section, we describe our parameterization strategy for 145 developing countries and for the entire set of 34 OECD countries modelled as a single entity.\textsuperscript{20} We use socio-demographic and economic data for 1980 and 2010, as well as socio-demographic prospects for the year 2040. For each country, our baseline trajectory matches the recent trends in human capital accumulation, income disparities, and population movements (including internal and international migrations). Table 1 summarizes the calibration outcomes.

Data. – We collect data on the socio-demographic and economic characteristics of 179 countries in the years 1980 and 2010. We use data on national Gross Domestic Product (GDP) for all countries from the Economic Research Service of the United States Department of Agriculture (USDA).\textsuperscript{21} Data on the agriculture share in the value added are taken from the Food and Agriculture Organization of the UN (FAOSTAT). As for the structure of the resident labor force by education level and by sector, we use the estimates described in Burzynski et al. (2018). Data on wages by education level are obtained from Biavaschi et al. (2016) for the nonagricultural sector, and from the Gallup World Polls for the agricultural sector.

We model international migration to OECD countries only. From the Database on Immigrants in OECD and non-OECD countries (DIOC), we extract the number of emigrants by education level to OECD countries for all countries in our sample and for the year 2010. The DIOC does not identify the region of origin of migrants (urban versus rural). However, for the majority of countries in our sample, skill- and region-specific information on the desire to emigrate can be extracted from the Gallup World Polls. Assuming the structure of migration aspirations is identical to the structure of actual emigration stocks, we split the number of emigrants to OECD countries by region of origin and by education level. As for urbanization, net internal migration is then the difference between the "before-migration" population ($N_{r,s,2010}$) in 2010 and the sum of the resident population and the international migrants ($\sum_{r,s}(L_{r,s,2010} + M_{r,f,s,2010})$) in 2010.

To proxy the average fertility rate ($\bar{n}_{1980}$), we divide the total native population of adults in 2010 ($\sum_{r,s} N_{r,s,2010}$) by the resident population of adults in 1980 ($\sum_{r,s} L_{r,s,1980}$).\textsuperscript{22} Moreover, our calibration requires data on the skill- and region-specific fertility for each country. By construction, we have $\bar{n}_t \equiv \sum_{r,s} L_{r,s,t} n_{r,s,t} / \sum_{r,s} L_{r,s,t}$. We use the Gallup World Polls and extract the Gallup-based average number of children per household in urban and rural regions by skill level for 2010. We compute the fertility of the college educated workers by fitting the sector-specific, low/high-skilled fertility differentials from

\textsuperscript{20}With the exceptions of Macao, North-Korea, Somalia and Taiwan, all countries that are not covered by our sample have less than 100,000 inhabitants.

\textsuperscript{21}For a few missing observations we impute values by making use of the Maddison database and data from the World Bank.

\textsuperscript{22}There is no mortality in the model. The average fertility rate at time $t$, $\bar{n}_t$, should be seen as a net population growth rate.
the Gallup database. In this way, we obtain the fertility rates for each country for the year 1980. From 2010 onwards, the number of children is endogenous.

**Technological parameters.** – Output in each sector depends on the size and skill structure of employment. To calibrate the set of technological parameters, we proceed in two steps.

First, we calibrate the parameters affecting the private returns to higher education. For each sector, we combine our estimates for $\ell_{r,t}$ with cross-country data on the income gap between college graduates and the less educated. We calibrate the elasticity of substitution between college graduates and less educated workers relying on existing studies. As for the nonagricultural sector, there is a large number of influential papers that propose specific estimates for industrialized countries (i.e., countries where the employment share of agriculture is small). Ottaviano and Peri (2012) suggest setting $\sigma_n$ close to 2.0. As for the agricultural sector, it is usually assumed that the elasticity of substitution is much larger. For example, Vollrath (2009) or Lucas (2009) assume perfect substitution between skill groups. In line with the existing literature, we assume $\sigma_n = 2$ and $\sigma_a = \infty$. Once the elasticities are chosen, we use our proxies for $\Gamma_{w,r,t}$ and $\Gamma_{n,r,t}$ using (3). Regressing the log of $\Gamma_{w,r,t}$ on the log of $\Gamma_{n,r,t}$ yields insignificant effect in agriculture, and a correlation of 0.38 in nonagriculture. We thus rule out the possibility of skill-biased technical change in agriculture ($\kappa_a = 0$), and assume a linear technology with a constant $\Gamma_{n,r,t} = 1$ for all countries and all periods. The value of $\Gamma_{w,r,t}$ is given by the population-weighted average of $\Gamma_{w,r,t}$, leading to $w_a = 0.57$. In nonagriculture, we assume that half the correlation is due to the skill-bias externality (i.e., $\kappa_n = 0.19$), and we calibrate $\Gamma_{n,r,t}$ as a residual from (5).

In the second step, we use data on income by sector in the year 2010 and identify the TFP levels ($A_{r,t}$) as a residual from Equation (1). There is a clear positive relationship between TFP and the skill ratio in both sectors. Indeed, regressing the log of $A_{r,t}$ on the log of $\Gamma_{n,r,t}$ gives a coefficient of 0.57 in the nonagricultural sector, and 0.66 in agriculture. We assume that half the correlation between TFP and the share of college-educated workers is due to the schooling externality (i.e., $\epsilon_n = 0.28$ and $\epsilon_a = 0.33$). We calibrate $\overline{A}_n$ as a residual from (4).

**Preference parameters.** – The literature indicates some common values of several preference parameters. We assign the following values to the parameters that are time-invariant and equal for all countries: $\theta = 0.25$, $\lambda = 0.5$ and $\phi = 0.14$. From (13) and (14), the scale parameter of the distribution of migration tastes ($\mu$) is the inverse of the elasticity of bilateral migration to the wage rate. Bertoli and Fernández-Huertas Moraga (2013) find a value between 0.6 and 0.7 for this elasticity. Hence, we use $\mu = 1.4$.

The parameters $\pi_r$ and $\psi_{r,t}$ affect the fertility and education decisions. We calibrate them to match the population dynamics between the years 1980 and 2010, i.e., the transition from the resident population in 1980 and the native population in 2010. From Equations (11) and (12), the fertility rate in the model depends on the product of $\pi_r \psi_{r,t}$. Once fertility rates are matched we are able to identity the product $\pi_r \psi_{r,t}$. We then calibrate $\pi_r$ and $\psi_{r,t}$ in order to match the educational structure of the native population in 2010, imposing the given value to the ratio of probabilities of becoming high-skilled across regions.

As for internal migration costs, we assume there is only migration from rural to urban.

---

23Given the expression in (9), this assumption reflects setting the bound of the maximal number of children equal to 7 (i.e., 14 children per couple). See Docquier et al. (2016) for a brief review of studies using similar parameter values.
regions (i.e., $x_{an,s,t} < 1$ and $x_{na,s,t} = 1$). We obtain internal migration costs for rural-urban migration from Equation (14). In order to determine the international migration costs ($x_{af,s,t}$ and $x_{nf,s,t}$), we begin by retrieving the utilities achievable abroad. We set these utilities equal to the skill-specific weighted average utilities of the OECD countries. The weights consist in the respective population sizes of the OECD countries. We then obtain the international migration costs from Equation (14).

To the best of our knowledge there is no information on the relative income loss experienced by individuals which are displaced by floods. However, in cases of armed conflicts, Fiala (2015) finds that displaced households incur a loss of consumption ranging between 28% and 35%. For Columbia, Ibanez and Moya (2006) find that a displacement is associated with a loss of 50% of income. Kellenberg and Mobarak (2011) characterize the willingness to pay for investments in disaster prevention to around 24% of income. We use these studies to proxy the expected income loss due to a climate-driven forced displacement. Given this micro evidence, we pessimistically assume $B = 0.5$ (i.e., relocating within the region of birth induces an income loss equal to 50% of the lifetime income).

**Projections.** – The philosophy of our baseline projection exercise is to predict the future trends in income, population and human capital if all parameters remain constant, with the exception of the parameters governing access to education. More precisely, we constrain our baseline trajectory to be compatible with medium-term official demographic projections, as reflected by the UN projections of the national adult population and proportion of college graduates for the year 2040. Hence, we allow for country-specific proportional adjustments in $\psi_{r,t}$ ($r = a, n$) (i.e., the same relative change in both sectors) that minimizes the sum of squared differences in population and human capital between the baseline simulations and the UN projections for the year 2040. Remember $\psi_{r,t}$ determines the cost of education in the region. Comparing the new levels of $\psi_{r,2010}$ with those obtained in 1980 (i.e., $\psi_{r,1980}$), we identify a conditional convergence process in the access to education. We see it as a likely consequence of the Millennium Development policy. We estimate two quadratic, region-specific convergence equations considering the US as the benchmark frontier: 

$$\ln (\psi_{r,t+1}/\psi_{r,t}) = \alpha_r + \beta_r \ln \left( \psi_{USA,t}^{USA}/\psi_{r,t} \right) + \gamma_r \left( \ln \left( \psi_{USA,t}^{USA}/\psi_{r,t} \right) \right)^2.$$ 

We obtain $\gamma_a = 0.032$, $\gamma_n = 0.046$, $\beta_a = -0.195$ and $\beta_n = -0.223$, where all parameters are highly significant.

For subsequent years, our baseline scenario assumes a continuation of this quadratic convergence process, in line with the new Sustainable Development Agenda. Under this assumption, Burzynski et al. (2018) show that the model simulations fit the official sociodemographic projections very well. This is a proof of concept that such a stylized model does a good job in generating realistic projections of population, human capital, and urbanization.

### 4 Results

In Section 4.1, we focuses on the three moderate CLC scenarios and study their economic and demographic impacts. Then, Section 4.2 discusses the results obtained under more extreme CLC scenarios. Finally, Section 4.3 discusses the role of international migration policies in limiting the inequality and poverty implications of CLC.
Table 1: Common and country-specific parameters

<table>
<thead>
<tr>
<th>Parameters without country variations</th>
<th>Description</th>
<th>Mean</th>
<th>s.d.</th>
<th>Source/Moment matches</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sigma_n )</td>
<td>Elast. subst. in nonagr.</td>
<td>2.00</td>
<td>-</td>
<td>Ottaviano &amp; Peri (2012)</td>
</tr>
<tr>
<td>( \sigma_a )</td>
<td>Elast. subst. in agr.</td>
<td>( \infty )</td>
<td>-</td>
<td>Vollrath (2009) or Lucas (2009)</td>
</tr>
<tr>
<td>( \epsilon_n )</td>
<td>Aggregate externality in nonagr.</td>
<td>0.28</td>
<td>-</td>
<td>Half corr. betw. ( \ln A_{n,t} ) &amp; ( \ln \Gamma_{n,t} )</td>
</tr>
<tr>
<td>( \epsilon_a )</td>
<td>Aggregate externality in agr.</td>
<td>0.33</td>
<td>-</td>
<td>Half corr. betw. ( \ln A_{a,t} ) &amp; ( \ln \Gamma_{a,t} )</td>
</tr>
<tr>
<td>( \kappa_n )</td>
<td>Skill-biased externality in nonagr.</td>
<td>0.19</td>
<td>-</td>
<td>Half corr. betw. ( \ln \Gamma_{n,t} ) &amp; ( \ln \Gamma_{n,t} )</td>
</tr>
<tr>
<td>( \kappa_a )</td>
<td>Skill-biased externality in agr.</td>
<td>0.00</td>
<td>-</td>
<td>Half corr. betw. ( \ln \Gamma_{a,t} ) &amp; ( \ln \Gamma_{a,t} )</td>
</tr>
<tr>
<td>( \theta )</td>
<td>Preference for children</td>
<td>0.25</td>
<td>-</td>
<td>Docquier et al. (2016)</td>
</tr>
<tr>
<td>( \lambda )</td>
<td>Elast. training technology</td>
<td>0.50</td>
<td>-</td>
<td>Docquier et al. (2016)</td>
</tr>
<tr>
<td>( \phi )</td>
<td>Time to raise a child</td>
<td>0.14</td>
<td>-</td>
<td>Docquier et al. (2016)</td>
</tr>
<tr>
<td>( \mu )</td>
<td>1/Elast. mig. to wages</td>
<td>1.40</td>
<td>-</td>
<td>Bertoli &amp; Fernández-Huertas Moraga (2013)</td>
</tr>
<tr>
<td>( B )</td>
<td>Income loss due to forced displ.</td>
<td>0.50</td>
<td>-</td>
<td>Fiala (2015) or Ibanez &amp; Moya (2006)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameters with some country variations</th>
<th>Description</th>
<th>Mean</th>
<th>s.d.</th>
<th>Source/Moment matches</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \overline{A}_n )</td>
<td>Scale factor in TFP</td>
<td>216,969</td>
<td>267,723</td>
<td>Residual from (4)</td>
</tr>
<tr>
<td>( \overline{A}_a )</td>
<td>Scale factor in TFP</td>
<td>89,025</td>
<td>320,698</td>
<td>Residual from (4)</td>
</tr>
<tr>
<td>( \pi_n )</td>
<td>Scale factor in skill bias</td>
<td>1.878</td>
<td>-</td>
<td>Residual from (3)</td>
</tr>
<tr>
<td>( \pi_a )</td>
<td>Scale factor in skill bias</td>
<td>1.326</td>
<td>-</td>
<td>Residual from (3)</td>
</tr>
<tr>
<td>( \pi_n )</td>
<td>Scale factor training technology</td>
<td>0.025</td>
<td>0.041</td>
<td>Match fertility/educ. in (11)</td>
</tr>
<tr>
<td>( \pi_a )</td>
<td>Scale factor training technology</td>
<td>0.043</td>
<td>0.142</td>
<td>Match fertility/educ. in (11)</td>
</tr>
<tr>
<td>( \psi_n )</td>
<td>Education cost</td>
<td>13.74</td>
<td>67.27</td>
<td>Match fertility/educ. in (11)</td>
</tr>
<tr>
<td>( \psi_a )</td>
<td>Education cost</td>
<td>46.22</td>
<td>148.98</td>
<td>Match fertility/educ. in (11)</td>
</tr>
<tr>
<td>( x_{an,h} )</td>
<td>Internal mig. cost, high-skilled</td>
<td>0.712</td>
<td>1.989</td>
<td>Match urbanization (WDI)</td>
</tr>
<tr>
<td>( x_{an,l} )</td>
<td>Internal mig. cost, low-skilled</td>
<td>0.928</td>
<td>0.163</td>
<td>Match urbanization (WDI)</td>
</tr>
<tr>
<td>( x_{af,h} )</td>
<td>International mig. cost, high-skilled</td>
<td>0.416</td>
<td>4.422</td>
<td>Match migration data (DIOC)</td>
</tr>
<tr>
<td>( x_{af,l} )</td>
<td>International mig. cost, high-skilled</td>
<td>0.829</td>
<td>1.065</td>
<td>Match migration data (DIOC)</td>
</tr>
<tr>
<td>( x_{af,l} )</td>
<td>International mig. cost, low-skilled</td>
<td>0.947</td>
<td>0.281</td>
<td>Match migration data (DIOC)</td>
</tr>
<tr>
<td>( x_{af,l} )</td>
<td>International mig. cost, low-skilled</td>
<td>0.985</td>
<td>0.066</td>
<td>Match migration data (DIOC)</td>
</tr>
</tbody>
</table>

4.1 Impact under moderate scenarios

We first consider the three moderate scenarios (Intermediate, Minimalist and Maximalist) defined in Section 2.1, and discuss the worldwide effects of CLC on income per capita, income inequality, population, human capital, urbanization and international migration. Then, we highlight the cross-country heterogeneity in the effect of CLC before quantifying internal and international migration responses.

Aggregate effects on the world economy. – The effects on the world economy are depicted in Figure 5. The worldwide responses are the weighted averages of the positive and negative effects observed in high-income and developing countries.

We first compare our Intermediate scenario (continuous black curve) to the Minimalist (dotted black curve) and to the Maximalist (dotted grey curve). CLC slightly increases the worldwide level of income per worker (Figure 5a), but makes the world distribution of income more unequal (Figure 5b). The former result is due to multiple factors. First,
higher temperature levels induce positive changes in TFP at high levels of latitude (where income per worker is initially higher) and negative changes in TFP close to the equator (where income per worker initially is lower). Second, in developing countries, CLC reallocates people from lower-productivity rural regions to higher-productivity urban regions, as illustrated in Figure 5e. Third, CLC reallocates people from poorer countries to richer countries, as illustrated in Figure 5f. The effects on the world population size and on the share of college graduates are small, as illustrated in Figure 5c and 5d. The mobility responses to CLC are slightly non linear: the difference between the Maximalist and Intermediate scenarios slightly exceeds the difference between the Intermediate and the Minimalist ones. On the contrary, the effects on income per worker and inequality are almost identical.

Country-specific effects. – The country-specific effects of CLC are depicted in Figure 6. We report the relative differences between the Intermediate and the Minimalist scenarios (black bubbles), as well as the relative differences between the Maximalist and the Intermediate scenarios (grey bubbles). Third-degree polynomial trends are represented in black and grey, respectively. Bubble sizes are proportional to the adult population size of each country in 2010. Figure 6a shows that CLC decreases income per worker by 15% in countries close to the equator, and increases it by 10% at high levels of latitude. Hence, the income gap between the richest and poorest countries increases by 25% in the course of the 21st century. Given the assumed timing of CLC, unreported results reveal that most of the effect occurs in the first half of the century. Assuming more gradual CLC, things would be different.

In developing countries, the negative effect on income is resulting from three mechanisms (in line with worldwide aggregate effects). The first one is the fall in TFP in both sectors, documented in Figure 2. The second effect is the rise in urbanization in Figure 6c, which attenuates the TFP shocks since the average level of labor productivity is greater in manufacturing than in agriculture. The third effect is the slight decrease in human capital illustrated on Figure 6b. Although urbanization increases the access to education in poor countries, rising international emigration (see Figure 6d) reduces human capital accumulation. The reason is that high-skilled people face smaller migration cost, which implies that migration is skill biased. In poor countries, college graduates migrate 20 times more than the less educated. CLC reduces the intensity of positive selection by 10% only, as shown on Figure 6f. Hence, the positive effect of CLC on emigration rates tends to reduce the share of college graduates in the origin country. For the sake of comparability, the effect of CLC on the skill bias in internal migration is similar to that of long-haul migration, as illustrated in Figure 6e. Overall, CLC has a greater impact on low-skilled mobility than on high-skilled mobility.

Comparing the Maximalist to the Intermediate scenario, and comparing Intermediate to the Minimalist give very similar results. The negative effect on income is slightly more pronounced in countries close to the equator when considering the Maximalist scenario. In addition, Figure 6c and 6d demonstrate that under the Maximalist scenario, urbanization and emigration responses are slightly greater. The human capital responses are on average almost identical. Table A1 in Appendix A.1 reports the effect of CLC on the country-wide level of income per worker for the 20 most adversely affected countries in the year 2100. Countries close to the equator experience a long-run decrease in income per worker which varies between 14% and 22% when the temperature increases by 2°C. The most affected countries include Sao Tome and Principe, the Gambia, Venezuela, Nepal,
Figure 5: Aggregate effects of CLC on the world economy

Notes: Simulation results based on the moderate CLC scenarios defined in Section 2.1.
Grenada, Nicaragua, Malaysia, the Dominican Republic, Ghana, the Philippines, and several African countries and Pacific islands.

The income loss is even greater for the poorest workers trapped in the poorest or falling regions (i.e., rural regions). Extreme poverty is usually measured as the percentage of population living with less than $1.90 per day in PPP value. Nevertheless, in our secular context with a constant rate of productivity growth and two skill groups only, we need to use a relative poverty line. We measure extreme poverty as the world percentage of adults below a relative poverty line that corresponds to 2% of the worldwide average level of income per worker.

Comparing the CLC scenarios, Figure 7a shows that CLC adversely impacts extreme poverty. In the Intermediate scenario, poverty headcounts mechanically increase over time. This is essentially due to the differential in population growth between poor and rich countries/regions. By the year 2100, we identify 621 million individuals in extreme poverty in the Intermediate scenario (about 13.2% of the world population). Under the Minimalist and Maximalist scenarios, the numbers amount to 517 and 835 million (i.e., 11.0% and 17.9% of the world population), respectively. In addition, Figure 7b shows that the intensity/depth of extreme poverty increases. The ratio of average income of the extreme poor to the worldwide average income decreases with CLC in all years. Hence, CLC influences extreme poverty at both extensive and intensive margins.

Figure 7c shows the effect of CLC on the relative income of the ten poorest groups on earth. We rank all classes of worker with respect to the ratio between their income level and the worldwide average level. The poorest people are low-skilled workers living in the rural region of the poorest countries. For instance, low-skilled workers in rural regions of Burundi earned around 0.54% of the global average income in the Intermediate scenario. This ratio reaches 0.65 in the Minimalist scenario and 0.42 in the Maximalist one. On average, the index of relative income of the poorest workers is divided by 1.5 when the temperature increases by 2°C.

Migration responses. – It is frequently claimed that CLC will create the world’s biggest international refugee crisis of all ages. In line with Figure 5f, our results in Table 2 suggest that this is unlikely to be the case. We predict that CLC will induce large displacements of people from vulnerable to more viable areas on Earth. However, most of them will move within their country. Compared to the Minimalist (no-CLC) scenario, rising temperature and sea level increases the number of adult movers by 78.4, 24.6 and 16.9 million people in 2040, 2170 and 2100 (i.e., by 2.1%, 0.6% and 0.4% of the world adult population, respectively). In the course of the 21st century, this amounts to a total of 120 million adults in the Intermediate scenario (we obtain 185 millions in the Maximalist scenario). Far more people are migrating within their own countries than across borders. In the Intermediate scenario, 66% of these movements are local displacements within the region of birth, 15% are movements between regions (from agriculture to nonagriculture), and only 19% are long-haul international movements from developing to OECD countries.

Hence, CLC increases the number of internal adult migrants by 97 millions (with 81% of internal displacements). In the Maximalist scenario, we obtain 135 millions (with 67% of local displacements). The numbers are very much in line with those reported in Rigaud et al. (2018), who predict that 65 to 145 million people of all ages could

\[24\] If the poverty line equals 1% of the worldwide average income level, 202 million workers will live in extreme poverty in 2100 under the Intermediate scenario (4.2% of the world population). This compares to 181 and 272 million workers (3.9% and 6.0%) under the more optimistic and pessimistic scenarios, respectively.
Figure 6: Country-specific effects by level of latitude

Notes: Simulation results based on the moderate CLC scenarios defined in Section 2.1. Latitude (geographic coordinate) is measured on the X-axis and bubble sizes are proportional to the population aged 25-64 in the year 2010. A few outliers are not depicted on Figures 6a, 6d and 6e.
Figure 7: Effect of CLC on extreme poverty in 2100

Notes: Simulation results based on the moderate scenarios defined in Section 2.1. The reported countries in Figure 7c include Burundi (BDI), Cameroon (CMR), Eritrea (ERI), Guinea (GIN), Mozambique (MOZ), Nepal (NPL), Tanzania (TZA), Timor-Leste (TLS), Togo (TGO), and Zimbabwe (ZWE).

migrate within their own countries to escape slow-onset impacts of climate change by the year 2050. Compared to this study, we offer additional insight on the international migration responses to CLC. We show that CLC increases the number of international adult migrants by 22.5 millions in the Intermediate scenario and by 51.3 millions in the Maximalist scenario. Although these numbers are non-negligible, they are small compared to the global changes in migration stocks.

Table A2 in Appendix A.2 reports emigration and immigration rates by region. As far as emigration is concerned, we show that CLC multiplies emigration rates by a factor of 1.05, which is a small fraction (between 1/10 and 1/20) of the total rise in emigration rates. Total changes in emigration rates are mostly explained by the changing educa-
tional attainment in the developing world: education makes people more migratory. As for immigration, the average share of immigrants should be multiplied by a factor of 1.5 in settlement countries (the US, Canada and Australia), and should increase twofold in Europe over the 21st century. However, the contribution of CLC to increasing immigration is small. CLC explains about 1/20 of the total change in the worldwide share of immigrants in the population. Total changes are mostly explained by demographic imbalances between rich and poor countries, and by education trends.

Table 2: Global numbers and shares of movers in 2040, 2070 and 2100
(Number in million of people and shares as % of world adult population)

<table>
<thead>
<tr>
<th></th>
<th>Number (in million)</th>
<th>As % world pop</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2040</td>
<td>2070</td>
</tr>
<tr>
<td>Intermediate minus Minimalist</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>78.4</td>
<td>24.6</td>
</tr>
<tr>
<td>Rural-Urban</td>
<td>13.1</td>
<td>4.1</td>
</tr>
<tr>
<td>International</td>
<td>6.4</td>
<td>6.9</td>
</tr>
<tr>
<td>Local</td>
<td>58.8</td>
<td>13.6</td>
</tr>
<tr>
<td>Flooded</td>
<td>69.4</td>
<td>15.5</td>
</tr>
<tr>
<td>Maximalist minus Minimalist</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>109.7</td>
<td>42.6</td>
</tr>
<tr>
<td>Rural-Urban</td>
<td>26.5</td>
<td>13.5</td>
</tr>
<tr>
<td>International</td>
<td>13.6</td>
<td>16.5</td>
</tr>
<tr>
<td>Local</td>
<td>69.8</td>
<td>12.7</td>
</tr>
<tr>
<td>Flooded</td>
<td>82.5</td>
<td>14.5</td>
</tr>
</tbody>
</table>

Notes: Simulation results based on the moderate CLC scenarios defined in Section 2.1.

4.2 Robustness to extreme CLC scenarios

It has been argued that we are in uncharted territory when predicting CLC as the effects of CO2 emissions on temperature and sea level are highly uncertain (Stern, 2003; Schelling, 2007). It is thus important to consider more extreme scenarios. This section defines four alternative scenarios and analyzes the sensitivity of our results to more extreme changes.

Definition of extreme scenarios. – Uncertainty about SLR is large as climate models have been unable until recently to replicate the estimated sea level swings reconstructed from geological data during the Pliocene (about 100,000 years ago) when concentrations were about the same as now, temperatures were 0-2°C higher and the sea level was 6-9m higher.\(^{25}\) The World Bank predicts a sea-level rise of 2m for the year 2050. For the purpose of comparison, we also consider an extreme SLR variant with a 2.7m rise by the end of the century, and a no-SLR scenario as a point of comparison.

Furthermore, two additional channels of transmission are frequently accounted for in the literature. Firstly, temperature variations may also cause direct utility effects through its impact on health or on the drudgery of work. Secondly, CLC can affect economic performance and migration decisions through conflicts over resources. We model these two additional channels as following:

\(^{25}\)De Conto and Pollard (2016) have calibrated the sea level swings of the Pliocene, projecting an increase in the sea level above 1m in 2100. They estimate that the Antarctica ice sheet cannot be saved even with extraordinary success at cutting emissions. This would lead to a locking of the sea level rise of more than 5m.
• To account for potential direct utility losses (due to the effect of temperature on health or on the drudgery of work), we follow Dell et al. (2014) who report estimates that output per worker decreases by 2% per 1°C increase when temperature exceeds 20°C. We assume that this effect is due to a decrease in effective labor supply driven by a greater disutility of labor. In a simple model with quasi-linear utility function and a constant elasticity of labor supply to the disutility of labor, relative variations in utility are proportional to relative variations in labor supply. As shown in Appendix A.3, assuming an elasticity of labor supply to income of 1/3, the optimal utility level decreases by 8% per 1°C increase in all regions where temperature exceeds 20°C. Although our model disregards the disutility of labor, we model utility losses similarly and assume \( \tau_{r,t} = 0.08(T_{r,t} - T_{r,2010}) \) if \( T_{r,t} > 20 \) and zero otherwise.

• In contexts of high political and social instability, CLC can contribute to the onset and propagation of (violent) conflicts driven by the deterioration of governance capacities and by the increase in inequality among groups (Miguel et al., 2004; Gleditsch, 2012). The relationship between CLC and conflict has been investigated in a number of studies, which have produced mixed results (Cattaneo et al., 2018). Using a hierarchical meta-analysis of 55 studies, Burke et al. (2015) find that deviations from moderate temperatures and precipitation patterns systematically increase conflict risk (including interpersonal conflict, such as assault and murder, and intergroup conflict, including riots and civil war). On average, one standard-deviation increase in temperature increases interpersonal conflict by 2.4% and intergroup conflict by 11.3%. In turn, conflicts lead to forced displacements. Dao et al. (2018) find that severe armed conflicts increase the dyadic stock of migrants twofold in the long-term. In our simulations, we assume that conflicts decrease net international migration costs in the poorest countries in such a way that their emigration stocks increase by a factor of 2, as explained in Appendix A.3.

In sum, to investigate the sensitivity of our results to extreme scenarios and additional channels of transmission, we consider four alternative scenarios:

• **Extreme-No SLR.** – Assuming constant seal level and a global increase in temperature of 2.09°C, this scenario neutralizes forced displacements. It can be considered as unrealistic and extreme, but we use it as a no-SLR point of reference.

• **Extreme-Greater SLR.** – While keeping a global increase in temperature of 2.09°C, we now assume a sharper sea-level rise over the 21st century. In line with Rigaud et al. (2018), our Greater SLR variant assumes that SLR reaches 2m in 2040. For subsequent periods, we assume the same relative changes as in the Intermediate scenario; this gives 2.4m in 2070 and 2.7m in 2100. This scenario induces a larger number of forcibly displaced people.

• **Extreme-Utility.** – In this scenario, we start from the Maximalist scenario and supplement it with direct utility losses. As stated above, we assume a direct utility loss of 8% per 1°C increase in all regions where temperature exceeds 20°C.

• **Extreme-Conflict.** – Here, we start from the Extreme-Utility scenario and assume that a long-term conflict arises in the ten countries with the highest poverty head-

\[26\] It increases the dyadic stock of migrants by a factor of 4 in the medium-term.
counts (i.e., Burundi, Cameroon, Eritrea, Guinea, Mozambique, Nepal, Tanzania, Timor-Leste, Togo, and Zimbabwe).

Results. – Aggregate implications for the world economy are depicted in Figure A2 in Appendix A.4. We focus here on the mobility responses to more extreme scenarios. Compared to the Intermediate scenario, considering extreme SLR (i.e., no SLR or a 2.7 m SLR by the end of the century) has a limited impact on worldwide migration responses, both internal and international. This means that variations in SLR mostly induce local displacements. In other words, the variations between the moderate scenarios reported in Table 2 are overwhelmingly explained by the effect of temperature on productivity. On the contrary, compared to the Maximalist scenario, accounting for direct utility losses (8% per 1°C increase above 20°C) or conflicts over resources (in ten countries with the greatest poverty headcounts) has a drastic impact on internal and international migration.

Table 3 characterizes the effect of direct utility losses and conflict on mobility patterns. The numbers can easily be compared with those of the Maximalist scenario in Table 2. Remember the Maximalist scenario predicts a total number of movers of 185 millions, including 51 million international migrants to the OECD member states. When adding the direct utility losses, we obtain 305 million movers (i.e., an increment of 120 millions) and 74 million international migrants (i.e., an increment of 23 millions). Table A4 in Appendix A.4 shows that, by the year 2100, the proportion of emigrants increases by 0.9 percentage point in Latin America, and by 0.6 percentage point in sub-Saharan Africa. As far as OECD destinations are concerned, the proportion of immigrants increases by 0.9 percentage point in the US and in the European Union.

When adding the conflict effect, we obtain 320 million movers (i.e., a new increment of 15 millions) and 89 million international migrants (i.e., a new increment of 15 millions). Severe conflicts impact international migration flows. By the year 2100, the proportion of emigrants increases by additional 0.4 percentage point in sub-Saharan Africa, where most conflict-affected countries are located. The resulting shares of immigration increase by 0.4 percentage point in the US and in the European Union. These numerical experiments reveal that conflicts over resources are likely to become a key determinant of climatic migration pressures, and that direct utility effects of CLC imply rather high uncertainty about their scale and their type.

4.3 Role of migration policies

We now investigate whether a change of immigration policies can help limiting the effect of CLC on extreme poverty. Starting from the Intermediate scenario, we simulate the effect of two policy options for two sets of origin countries. The first option consists of preventing people to emigrate from 2040 on ($x_{r,F,s,t} = 1$); the second one consists of reducing international migration cost by 5% ($x_{r,F,s,t} ightarrow 0.95 \cdot x_{r,F,s,t}$). Figure 8 shows the effect of these two policy reforms on the world proportion of people whose income is smaller than the relative poverty line (i.e., 2% of the world average level of income per worker). As far as the target group is concerned, Figure 8a shows the effect obtained when the policy affects all workers living in the ten countries with the largest shares of population in extreme poverty (those reported in Figure 7c). Figure 8b shows the effect obtained when the policy is restricted to low-skilled workers living in the rural region of the same ten poorest countries. Figure 8c shows the effect obtained when the policy affects all workers living in the twenty most affected countries by CLC (those listed in
Table 3: Global numbers and shares of movers under extreme scenarios
(Numbers in million of people and shares as % of world adult population)

<table>
<thead>
<tr>
<th></th>
<th>Number (in million)</th>
<th>As % world pop</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2040</td>
<td>2070</td>
</tr>
<tr>
<td>Extreme-Utility minus Minimalist</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>158.8</td>
<td>87.5</td>
</tr>
<tr>
<td>Rural-Urban</td>
<td>71.0</td>
<td>50.1</td>
</tr>
<tr>
<td>International</td>
<td>18.1</td>
<td>24.7</td>
</tr>
<tr>
<td>Local</td>
<td>69.7</td>
<td>12.7</td>
</tr>
<tr>
<td>Flooded</td>
<td>82.7</td>
<td>14.5</td>
</tr>
<tr>
<td>Extreme-Conflict minus Minimalist</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>162.1</td>
<td>92.1</td>
</tr>
<tr>
<td>Rural-Urban</td>
<td>72.0</td>
<td>49.8</td>
</tr>
<tr>
<td>International</td>
<td>20.3</td>
<td>29.7</td>
</tr>
<tr>
<td>Local</td>
<td>69.7</td>
<td>12.7</td>
</tr>
<tr>
<td>Flooded</td>
<td>82.7</td>
<td>14.6</td>
</tr>
</tbody>
</table>

Notes: Simulation results based on the extreme scenarios defined in this section.

Table A1 in Appendix A.2). Figure 8d shows the effect obtained when the policy affects low-skilled workers living in the rural region of the same twenty most affected countries.

In all cases, reinforcing migration restrictions has little effects on extreme poverty, which means that the current laws and policies are already highly restrictive. As for the relaxation of migration restrictions, its effectiveness is highly sensitive to the target group. When the policy affects the poorest individuals from the poorest countries, it decreases sensibly the worldwide extreme poverty headcounts. If the policy affects all workers, the effect is negligible. This is due to skill-selection in international migration responses. The relaxation policy mostly benefits high-skilled workers in the urban sector. 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 in the rural sector. When targeting countries that are strongly impacted by CLC, the effect of relaxing migration restrictions on extreme poverty is detrimental if affecting all groups of workers, and very slightly beneficial if affecting low-skilled workers in agriculture.

5 Conclusion

In the course of the 21st century, climate change will increase the income gap between the richest and poorest countries by about 25%. It will also influence extreme poverty at both extensive and intensive margins, and force millions of adults to flee their flooded area of residence. These are favorable conditions for increasing the international mobility of workers. In this paper, we endogenize the migration responses to climate change at various spatial scales. Our model relies on consensus micro-foundations, and is calibrated to match international and urbanization data of the last 30 years. Assuming a moderate scenario, we predict that climate change will lead to voluntary and forced movements of about 120 million working-age individuals and their children (i.e., around 200 individuals) during the 21st century. Nevertheless, more than 80% of them will move internally while 19% will opt for long-haul migration to an OECD destination. Under current migration laws and policies, far more climate migrants will move within their own countries than across borders. These migrants are mostly originating from countries that have contributed the
least to climate change, but experience the most damaging effects. However, our results also reveal that international migration is a costly adaptation strategy of last resort. This results hold when considering more extreme temperature and SLR scenarios: the number of displaced people increases but most of them move locally. Larger amounts of internal and international migration can be obtained when adding direct utility losses – which is a difficult mechanism to quantify – or conflicts over resources – which are more uncertain.

As far as policy implications are concerned, our results illustrate the difficulty to define a status of climate refugee. In our median scenario, about 85% of forcibly displaced persons will move internally. In addition, half of non-local movements – and 95% of international movements – are caused by climate-driven deterioration of economic and social conditions. Things look clearer when CLC induce conflicts although in practice, the link between CLC and conflict can be hard to establish. For example, the thesis of a Syrian ”climate war” has been challenged in the literature (Fröhlich, 2016; Selby et al., 2017). Hence, climate change is an additional factor that calls for better coherence between migration, development and environmental policies. Given people’s difficulty to emigrate from the poorest countries, preventive measures are needed to encourage climate change adaptation, local disaster-risk reduction, sustainable development in general, and

Figure 8: Poverty effects of relaxing immigration restrictions

Notes: Simulation results based on the Intermediate scenarios.
urban sustainable development in particular.

References


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A Appendix

A.1 Temperature scenarios

The CCKP projections are organized in 20-year climatological windows for the years 2020-2039, 2040-2059, 2060-2079, and 2080-2099. These projections are obtained from the Coupled Model Intercomparison Project Phase 5 (CMIP5) distribution (Taylor et al., 2012) which distinguishes between several scenarios for the Representative Concentration Pathways (RCP) (Moss et al., 2010). The median-emission scenario is called RCP-4.5. In addition, for each RCP, the CCKP provides data for 16 models obtained from different research institutes. Figure A1a depicts the evolution of the worldwide mean surface-temperature predicted by each of the 16 models of the median (RCP-4.5) package. The dashed black curve describes our baseline scenario. Overall, all models under RCP-4.5 predict an increase in temperature levels.

We proceed to two adjustments before plugging the temperature data into our model:

- Firstly, the climate literature suggests that aggregate (unweighted) country levels of temperature may not reflect accurately the impact of CLC (Dell et al., 2014). Particularly in large countries with regions of heterogeneous population densities, the aggregate measure poorly captures the intensity of the phenomenon. Hence, in a second step, we weight the monthly future temperature levels by population. To do this, we extract from the CCKP the monthly mean air temperature levels for the climatological window for the years 1991-2015. We weight equally the monthly observations to obtain a yearly temperature level for each country. Furthermore, Dell et al. (2012) provide a data set with population-weighted data on temperature levels. We compute the country-specific averages of these temperature levels for the years between 1995 and 2005. We then construct a scale factor for each country by dividing these population-weighted temperature levels by the temperature levels from the CCKP. In order to obtain future population-weighted measures, we multiply each of the monthly temperature levels for the future 20-year climatological windows with the country-specific scale factor.

- Secondly, the OLG model described in Section 3 must be fed with data in 30-year intervals (a period that is meant to represent the length of one generation), starting in 2010. Therefore, our third step consists in allocating the 20-year climatological windows to fit the temporal structure of the model. We assimilate the 2040-2059 climatological window to the year 2040, the 2060-2079 climatological window to the year 2070, and the 2080-2099 climatological window to the year 2100, respectively. In this way we obtain monthly population-weighted levels of temperature for the 179 countries in our data set. When averaged over all countries and months, our baseline temperature data predicts an increase in global temperature of 2.09°C by the end of the 21st century.27

A.2 Additional results for moderate scenarios

Table A1 gives the effect of CLC on the country-wide level of income per worker for the 20 most adversely affected countries (the ranking is based on the effect in the year 2100). It

27 Under the RCP-4.5 scenario the projected anomalies range from 0.83°C for the minimalist model of the 16 models to 3.20°C for the maximalist model as illustrated on Figure A1a.
documents the relative difference in income per worker between the *Intermediate* and the *Minimalist* scenarios, and between the *Maximalist* and the *Intermediate* scenarios. The table shows that poorer countries close to the equator experience a substantial decrease in income per worker in the long-term.

Table A1: Most adversely affected countries in 2040 and 2100 (as % of dev.)
(Ranking based on income per worker in 2100)

<table>
<thead>
<tr>
<th>Country</th>
<th>Interim/Minim 2040</th>
<th>Interim/Minim 2100</th>
<th>Maxim/Interm 2040</th>
<th>Maxim/Interm 2100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sao Tome and Principe</td>
<td>-17.8</td>
<td>-19.9</td>
<td>-20.1</td>
<td>-22.5</td>
</tr>
<tr>
<td>Gambia</td>
<td>-11.7</td>
<td>-18.2</td>
<td>-15.1</td>
<td>-21.7</td>
</tr>
<tr>
<td>Venezuela</td>
<td>-13.8</td>
<td>-17.8</td>
<td>-16.4</td>
<td>-20.8</td>
</tr>
<tr>
<td>Nepal</td>
<td>-15.9</td>
<td>-17.3</td>
<td>-16.8</td>
<td>-19.7</td>
</tr>
<tr>
<td>Grenada</td>
<td>-13.4</td>
<td>-17.1</td>
<td>-16.0</td>
<td>-19.6</td>
</tr>
<tr>
<td>Nicaragua</td>
<td>-15.3</td>
<td>-16.8</td>
<td>-18.9</td>
<td>-19.4</td>
</tr>
<tr>
<td>Malaysia</td>
<td>-14.3</td>
<td>-16.7</td>
<td>-18.1</td>
<td>-19.3</td>
</tr>
<tr>
<td>Dominican Republic</td>
<td>-13.5</td>
<td>-16.6</td>
<td>-17.5</td>
<td>-18.9</td>
</tr>
<tr>
<td>Ghana</td>
<td>-15.9</td>
<td>-16.5</td>
<td>-15.3</td>
<td>-18.6</td>
</tr>
<tr>
<td>Philippines</td>
<td>-15.3</td>
<td>-16.4</td>
<td>-16.1</td>
<td>-18.4</td>
</tr>
<tr>
<td>El Salvador</td>
<td>-13.9</td>
<td>-16.0</td>
<td>-18.1</td>
<td>-17.9</td>
</tr>
<tr>
<td>Cuba</td>
<td>-12.6</td>
<td>-15.4</td>
<td>-21.7</td>
<td>-17.6</td>
</tr>
<tr>
<td>Liberia</td>
<td>-18.6</td>
<td>-15.3</td>
<td>-15.2</td>
<td>-17.5</td>
</tr>
<tr>
<td>Fiji</td>
<td>-11.9</td>
<td>-15.0</td>
<td>-17.0</td>
<td>-17.2</td>
</tr>
<tr>
<td>Brunei Darussalam</td>
<td>-14.4</td>
<td>-14.8</td>
<td>-14.4</td>
<td>-17.2</td>
</tr>
<tr>
<td>Gabon</td>
<td>-12.5</td>
<td>-14.6</td>
<td>-15.0</td>
<td>-16.7</td>
</tr>
<tr>
<td>Guyana</td>
<td>-14.2</td>
<td>-14.3</td>
<td>-18.6</td>
<td>-16.6</td>
</tr>
<tr>
<td>Belize</td>
<td>-14.2</td>
<td>-14.1</td>
<td>-18.0</td>
<td>-16.2</td>
</tr>
<tr>
<td>Equatorial Guinea</td>
<td>-14.5</td>
<td>-14.0</td>
<td>-15.6</td>
<td>-16.1</td>
</tr>
<tr>
<td>Barbados</td>
<td>-12.5</td>
<td>-13.8</td>
<td>-15.2</td>
<td>-16.0</td>
</tr>
</tbody>
</table>

Notes: Simulation results based on the moderate CLC scenarios defined in Section 2.1.

Table A2 reports emigration and immigration rates by region. The top panel shows that the mean emigration rates from the developing world will increase during the 21st
century. The regional emigration rates will be multiplied by a factor of 1.5 to 2. This can be explained by the rise in education (highly educated people are more mobile) and by CLC. To identify the effect of CLC, the last two columns compare the predictions of the two alternative CLC scenarios in the year 2100. Comparing the Intermediate to the Minimalist and Maximalist scenarios, CLC affects the emigration rates from Latin America and, to a lesser extent, from Asia and sub-Saharan Africa. However, on average, CLC multiplies emigration rates by a factor of 1.05, which is a small fraction of the total rise in emigration rates.

The bottom panel documents the change in the proportion of immigrants in selected OECD countries. Remember we assume emigrants to the OECD aggregate entity are allocated across countries on the basis of the dyadic shares of the year 2010. Over the 21st century and at current migration policies and laws, the average share of immigrants should be multiplied by a factor of 1.5 in settlement countries (the US, Canada and Australia), and should increase twofold in Europe. These changes are mostly explained by demographic imbalances and by the progress in education. Comparing the CLC scenarios for the year 2100, we show that the contribution of CLC to increasing immigration is small. CLC explains about 1/20 of the total change in the share of immigrants in the population. The rise in the sea level induces minor effects on international migration, as most of the forcibly displaced people will relocate locally.

Table A2: International migration rates under moderate scenarios
(Emig. as % of native pop, Immig. as % of resident pop 25-64)

<table>
<thead>
<tr>
<th></th>
<th>Intermediate</th>
<th>Minimalist</th>
<th>Maxim.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2010 2040 2070 2100</td>
<td>2100 2100</td>
<td></td>
</tr>
<tr>
<td>Emigration rates</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Latin America</td>
<td>3.8 5.3 6.1 6.7</td>
<td>6.3 6.7</td>
<td></td>
</tr>
<tr>
<td>Sub-Saharan Africa</td>
<td>1.3 1.8 2.1 2.2</td>
<td>2.0 2.2</td>
<td></td>
</tr>
<tr>
<td>MENA</td>
<td>2.8 4.0 4.3 4.6</td>
<td>4.4 4.6</td>
<td></td>
</tr>
<tr>
<td>Asia</td>
<td>1.1 1.9 2.5 3.0</td>
<td>2.8 3.0</td>
<td></td>
</tr>
<tr>
<td>OECD</td>
<td>4.7 5.6 5.2 4.7</td>
<td>4.8 4.7</td>
<td></td>
</tr>
<tr>
<td>Immigration rates</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>United States</td>
<td>16.0 21.4 23.0 23.1</td>
<td>22.7 23.6</td>
<td></td>
</tr>
<tr>
<td>Canada</td>
<td>18.7 26.5 28.5 28.4</td>
<td>28.2 28.6</td>
<td></td>
</tr>
<tr>
<td>Australia</td>
<td>24.9 29.4 29.2 28.1</td>
<td>27.8 28.5</td>
<td></td>
</tr>
<tr>
<td>European Union</td>
<td>12.1 18.6 21.9 23.6</td>
<td>23.2 24.1</td>
<td></td>
</tr>
<tr>
<td>EU15</td>
<td>13.6 20.3 23.3 24.6</td>
<td>24.2 25.1</td>
<td></td>
</tr>
<tr>
<td>Germany</td>
<td>15.0 22.5 25.4 26.4</td>
<td>26.1 26.8</td>
<td></td>
</tr>
<tr>
<td>France</td>
<td>12.2 18.8 20.5 22.1</td>
<td>21.6 22.6</td>
<td></td>
</tr>
<tr>
<td>United Kingdom</td>
<td>14.6 22.2 25.4 26.6</td>
<td>26.3 26.9</td>
<td></td>
</tr>
<tr>
<td>Italy</td>
<td>10.9 17.2 20.6 22.5</td>
<td>21.9 23.1</td>
<td></td>
</tr>
<tr>
<td>Spain</td>
<td>14.0 20.6 23.3 24.3</td>
<td>23.8 24.8</td>
<td></td>
</tr>
</tbody>
</table>

Notes: Simulation results based on the moderate scenarios defined in Section 2.1.

Table A3 lists the countries with the highest emigration responses to CLC for the years 2040 and 2100. In 2040, countries that send the greatest numbers of emigrants abroad under the more pessimistic scenarios are usually those with higher fractions of forcibly displaced workers and/or those located close to the equator. By the end of the century,
these general results do not markedly change. Some of the small Caribbean islands are among the group of the most adversely affected economies in the year 2100.\footnote{Interestingly, Micronesia is among the top positively affected countries in the short-run and the top negatively affected countries in the long-run.}

Table A3: Largest changes in the stock of emigrants (as % of dev) (Ranking based on 2100)

<table>
<thead>
<tr>
<th>Country</th>
<th>Base/Opti</th>
<th>Country</th>
<th>Pess/Base</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2040</td>
<td>2100</td>
<td>2040</td>
</tr>
<tr>
<td>Bot 01</td>
<td>17.0</td>
<td>-15.6</td>
<td>Guyana</td>
</tr>
<tr>
<td>Bot 02</td>
<td>17.3</td>
<td>-13.1</td>
<td>Suriname</td>
</tr>
<tr>
<td>Bot 03</td>
<td>13.5</td>
<td>-9.5</td>
<td>Grenada</td>
</tr>
<tr>
<td>Bot 04</td>
<td>7.8</td>
<td>-8.9</td>
<td>Tonga</td>
</tr>
<tr>
<td>Bot 05</td>
<td>-10.3</td>
<td>-8.0</td>
<td>Russia</td>
</tr>
<tr>
<td>Bot 06</td>
<td>23.8</td>
<td>-6.5</td>
<td>Micronesia</td>
</tr>
<tr>
<td>Bot 07</td>
<td>10.6</td>
<td>-6.5</td>
<td>Samoa</td>
</tr>
<tr>
<td>Bot 08</td>
<td>10.9</td>
<td>-6.3</td>
<td>Russia</td>
</tr>
<tr>
<td>Bot 09</td>
<td>-9.4</td>
<td>-5.2</td>
<td>Samoa</td>
</tr>
<tr>
<td>Bot 10</td>
<td>-6.5</td>
<td>-4.3</td>
<td>Mongolia</td>
</tr>
<tr>
<td>Bot 11</td>
<td>11.4</td>
<td>-4.2</td>
<td>Fiji</td>
</tr>
<tr>
<td>Bot 12</td>
<td>11.0</td>
<td>-4.2</td>
<td>St Vinc &amp; Gren</td>
</tr>
<tr>
<td>Bot 13</td>
<td>6.1</td>
<td>-3.7</td>
<td>Cape Verde</td>
</tr>
<tr>
<td>Bot 14</td>
<td>10.4</td>
<td>-3.4</td>
<td>Lesotho</td>
</tr>
<tr>
<td>Bot 15</td>
<td>-4.3</td>
<td>-3.0</td>
<td>Belarus</td>
</tr>
<tr>
<td>Bot 16</td>
<td>-5.4</td>
<td>-2.4</td>
<td>Afghanistan</td>
</tr>
<tr>
<td>Bot 17</td>
<td>-2.3</td>
<td>-1.7</td>
<td>Bosnia Herz</td>
</tr>
<tr>
<td>Bot 18</td>
<td>10.9</td>
<td>-1.6</td>
<td>Ukraine</td>
</tr>
<tr>
<td>Bot 19</td>
<td>-4.9</td>
<td>-1.4</td>
<td>Albania</td>
</tr>
<tr>
<td>Bot 20</td>
<td>-3.3</td>
<td>-1.1</td>
<td>Serbia</td>
</tr>
</tbody>
</table>

Notes: Simulation results based on the moderate scenarios defined in Section 2.1.

A.3 Modeling utility losses and conflicts

To account for potential direct utility losses due to the effect of temperature on health or on the drudgery of work, we follow Dell et al. (2014) who report estimates that output per worker decreases by 2% per 1°C increase when temperature exceeds 20°C. We assume that this effect is due to a decrease in effective labor supply driven by a greater disutility of labor.

In a model with a quasi-linear utility function,

\[ U = wl - \frac{\varphi l^{1+\varphi}}{1+\varphi} \]

we have

\[ l = \left( \frac{w}{\varphi} \right)^{1/\varphi} \]

\[ \frac{\Delta U}{U} = (1 + \varphi) \frac{\Delta l}{l}. \]

Assuming a conservative value of 3 for \( \varphi \) (a labor supply elasticity to income of 1/3), we have \( \frac{\Delta U}{U} = 4 \frac{\Delta l}{l} = 8 \Delta T \) when temperature exceeds 20°C.
To account for the effect of conflicts over resources, we follow Dao et al. (2018) who show that severe armed conflicts increase the emigration stock twofold in the long-term. In our model, migration decisions from region $r^*$ are governed by:

$$N_{r^*,s,t} = M_{r^*,r,s,t} + M_{r^*,f,s,t} = M_{r^*,r,s,t}(1 + m_{r^*,r,s,t} + m_{r^*,f,s,t}),$$

where $m_{r^*,f,s,t} = (v_{r^*,f,s,t}/v_{r^*,r,s,t})^{1/\mu} (1 - x_{r^*,f,s,t})^{1/\mu}$ denotes the migrant-to-stayer ratio, and $N_{r^*,s,t}$ is the native (pre-migration) population (given at the beginning of each period). We can express the emigrant stock as:

$$M_{r^*,f,s,t} = m_{r^*,f,s,t} M_{r^*,r,s,t} = m_{r^*,f,s,t} N_{r^*,s,t} \frac{1}{1 + m_{r^*,r,s,t} + m_{r^*,f,s,t}}.$$

Everything else equal, we constrain $M_{r^*,f,s,t}$ to increase by a factor of 2 after the conflict (i.e. $\overline{M}_{r^*,f,s,t} = 2M_{r^*,f,s,t}$). Assuming (i) it affects high- and low-skilled workers symmetrically, and (ii) it affects all regions symmetrically, the conflict does not impact the relative attractiveness of rural and urban areas (i.e. $m_{r^*,r,s,t}$ is constant). We have to find the new level of $\overline{m}_{r^*,f,s,t}$ that is compatible with $\overline{M}_{r^*,f,s,t}$. The solution is:

$$\overline{m}_{r^*,f,s,t} N_{r^*,s,t} \frac{1}{1 + m_{r^*,r,s,t} + \overline{m}_{r^*,f,s,t}} = 2m_{r^*,f,s,t} N_{r^*,s,t} \frac{1}{1 + m_{r^*,r,s,t} + m_{r^*,f,s,t}},$$

$$\Rightarrow \overline{m}_{r^*,f,s,t} = \frac{2m_{r^*,f,s,t}(1 + m_{r^*,r,s,t})}{1 + m_{r^*,r,s,t} - m_{r^*,f,s,t}} = Z_{r^*,f,s,t} m_{r^*,f,s,t}.$$

Considering that the effect of the conflict is governed by a change in migration costs and net amenities ($x_{r^*,f,s,t} \rightarrow \overline{x}_{r^*,f,s,t}$), this requires

$$(1 - \overline{x}_{r^*,f,s,t}) = (1 - x_{r^*,f,s,t}) Z_{r^*,f,s,t} \mu.$$

### A.4 Additional results for extreme scenarios

The effects on the world economy are depicted in Figure A2, which reports results from the Intermediate scenario of Section 2.1 and those of the extreme scenarios defined in Section 4.2. The worldwide responses are the weighted averages of the positive and negative effects observed in high-income and developing countries.

Overall, considering extreme SLR scenarios (i.e., no SLR or a $2.7m$ SLR) has negligible impacts on worldwide responses. Changes in SLR slightly influence the share of international migrants in the year 2040. On the contrary, accounting for direct utility losses (8% per 1°C increase above 20°C) or conflicts over resources (in ten countries with the greatest CLC-driven changes in poverty headcounts: Burundi, Cameroon, Eritrea, Guinea, Mozambique, Nepal, Tanzania, Timor-Leste, Togo, and Zimbabwe) has a drastic impact on urbanization, international migration and income. Greater propensity to move, internally or internationally, increases the share of people living in cities and OECD countries. This explains why income per capita increases.

Table A4 reports emigration and immigration rates by region by the year 2100. The top panel shows that direct utility losses and conflict increase emigration rates by 0.9 percentage points in Latin America. The effect of SLR is negligible, confirming that forcibly displaced people migrate internally or locally. The bottom part of the table shows that immigration rates in OECD countries are very robust to SLR. On the contrary, they increase by 0.5 to 1 percentage point when direct utility losses and conflicts are accounted for.
Figure A2: Aggregate effects of CLC under extreme scenarios

Notes: Simulation results based on the more extreme scenarios defined in Section 4.2.
Table A4: International migration rates under extreme scenarios
(Emig. as % of native pop, Immig. as % of resident pop 25-64)

<table>
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<tr>
<th>Region</th>
<th>Interm. 2100</th>
<th>No SLR 2100</th>
<th>Great SLR 2100</th>
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<th>Conflict 2100</th>
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Notes: Simulation results based on the more extreme scenarios defined in Section 4.2.