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Go where the wind does not blow: Climate damages heterogeneity and future migrations*

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Abstract

In the context of climate change, migration can be considered as an adaptation strategy to reduce populations' exposure to climate damages. Those damages are very heterogeneous across regions. In this paper, we study migration induced by climate change damages. To do so, we estimate the socio-economic determinants of migration, focusing on economic damages. We then model endogenous migration in an integrated assessment model based on those estimates. We highlight the importance of the heterogeneity of the damages distribution to explain migration flows due to climate change. We find that high levels of climate damages globally do not necessarily induce large climate migration. Rather, large differences in exposure between regions may lead to substantial migration.

Keywords: Climate Change, Damage, Migration, Integrated Assessment Model

JEL classification: Q51, Q54, J11, F22

1. Introduction

Migrations related to climate events and climate change have attracted a lot of attention in the public debate. Given the importance of the potential effects of migration on well-being at the global level, it seems crucial to better understand how future environmental change may affect international migration patterns. Global policy to fight climate change should be designed to address the possible negative effects of migration.

Migration decisions are often multi-causal, and rarely due to environmental stress alone, but there is a consensus that one should consider the environmental impacts as one of the many factors that influence migration (Black et al., 2008; Black et al., 2013; Birk and Rasmussen, 2014; Millock, 2015). The literature has found inconsistent findings regarding the link between climate change and migration, with international migration increasing with higher temperature on the one hand (Backhaus et al., 2015; Cai et al., 2016; Cattaneo and Peri, 2016), and no relationship being found in other work (Beine and Parsons, 2015). Part of the literature has focused on the direct link between environmental variables (such as rainfall, temperature, sea-level rise, natural disasters, etc.) and migration trends (see Millock, 2015 or Cattaneo et al., 2019 for a literature review). Another strand of work has explored the indirect effect

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of environmental changes through economic variables (income, wages, resource depletion), as climate damages may increase the incentives to migrate for economic reasons (Rigaud et al., 2018; Cattaneo and Peri, 2016; Coniglio and Pesce, 2015). Beine and Parsons (2015) highlight that slow-onset events due to climate change have an indirect effect on migration through wages. However, even considering only the indirect channel, the effect of climatic factors on the mediators is not homogeneous. Cattaneo and Peri (2016), for instance, report increased migration with higher temperature in middle-income countries, whilst migration is suppressed in low-income countries. There are several potential reasons for those contrasting effects. First, climate damages may not only act as a push factor by increasing the incentives to migrate, but also as a pull factor if they occur in receiving countries, because they reduce economic opportunities there. Also, if the wealth of developing countries decreases due to climate change, people could be trapped in their origin country (McLeman, 2019). The overall effect of climate change on migration is thus ambiguous

To understand future international migration due to climate change, it is important to account for the differential economic damages across countries, and for the role of diasporas in reducing the cost of migration and increasing migration flows (Beine et al., 2011). In this paper, we build a model where we represent the endogenous effects of climate damages and the dynamics of diasporas to explain future excess migration due to climate change. More specifically, we use an Integrated Assessment Model (IAM), based on the work by Nordhaus (Nordhaus, 2018a), but adding endogenous population dynamics through mortality and migration. Our paper builds on Pottier et al. (2021), which introduces endogenous population dynamics in an integrated assessment model, focusing on the role of climate change-related mortality. We extend their model to also include endogenous migration. We account for mortality impacts: through migration, people may face lower climate related mortality risks, but, we find a very small impact of climate damages on mortality, with a variation in population of less than 0.1%. Therefore, in this paper we focus our attention and discussion on the migration dynamics, knowing that the main mechanisms related to health impacts have been extensively described in this previous work.

Different regions face different level of climate damages, thus inducing different regional migration patterns. Also, given that all regions are affected, climate change acts both as a push and a pull factor, and the dominating effect depends on the regional distribution of damages. The aim of the paper is to assess those heterogeneous regional effects.

A first step is to estimate the socio-economic determinants of migration. We seek to represent the effects of differences in regional income (that are affected by climate damages) and diasporas. Using combined data from the United Nations Population Division (International Migrant Stock, 2020; World Population Prospects) and other sources (World Development Indicators; CEPII dataset for gravity models), we regress a gravity model (Beine et al., 2016) that includes as main explanatory variables the ratio of Gross Domestic Product (GDP) between the sending and the origin region, the population size in both regions, the diaspora of the sending region residing in the receiving one, as well as some time-invariant characteristics. According to our analysis, the two main significant determinants are the ratio of GDP – which captures the potential gain from migration – and the size of the diaspora – which alleviates the cost of migration thanks to networks effects.

A second step is to include those estimates in an Integrated Assessment Model. These models usually do not include endogenous population dynamics. We model both endogenous baseline migration (without climate changes) and migration when climate damages are accounted for. We represent two sets of endogenous variables: GDP per capita and the size of the diasporas. To do so, we follow the narratives of the Shared Socioeconomic Pathways (SSP), and reproduce the "Middle of the road" scenario, where the world follows a path which maintains main historical patterns, *i.e.*, unequal development and income growth between regions (Fricko et al., 2017). This baseline scenario features a rise in temperature of 3.5°C by 2100. This temperature increase corresponds to the RCP8.5 scenario. We can assess the effect of climate change on migrations by comparing migrations in the hypothetical scenario where there are no climate damages, and the realistic scenario where there are climate damages.

One issue is that there is no consensus in the literature on the extent and spatial distribution of climate damages. Many authors use the estimate of damages by Nordhaus (2018b), but those result in limited impacts (specifically, a decrease in global income of 2.1 percent at 3°C warming). This has been criticized by several authors, and an empirical literature has developed to try to better estimate those damages. We thus consider two other specifications of climate damages: one from Burke et al. (2015) (who develop a method introducing a non-linearity in the response of productivity to temperature increase), and one from Kalkuhl and Wenz (2020) (who use a panel regression to identify the temperature's effect on productivity levels and growth). Those specifications differ from that of Nordhaus', both because they predict much higher damages, and, in the case of Burke et al. (2015), because they predict very heterogeneous effects across world regions.

The main objective of the paper is to highlight the importance of the distribution of future climate impacts for future climate-related migrations. We find that with Nordhaus (2018b) and Kalkuhl and Wenz (2020) damage functions, additional migration related to climate damages is almost null. This is because both damage distributions do not change the relative wealth of regions. More specifically, according to Kalkuhl and Wenz (2020)' estimates, Northern America is quite affected by climate damages, so immigration there decreases. On the contrary, with the damages projection from Burke et al. (2015), migrations flows increase by 10%. This is explained by the very contrasted effects of climate change across regions: some regions (especially in Europe) may actually gain, while others lose large shares of their GDP. Our aim is not to provide precise numbers for excess migration flows due to climate change, but to highlight the crucial role of the heterogeneity in climate impacts. To the best of our knowledge, there has been only one work (Benveniste et al., 2020) that has produced a similar analysis. The authors introduce a gravity model of migration in an integrated assessment model, and include remittances, *i.e.*, monetary transfers between the diaspora and individuals who have remained in their origin regions. The authors quantify future migration changes related to climate change, and find that migration might increase by 0.3 to 1.1% by the end of the century. Their results are therefore in line with those we obtain using damage estimates from Nordhaus (2018b) or Kalkuhl and Wenz (2020). The difference with our paper is our specific focus on the role of the heterogeneity of climate damages, and on the role of diasporas.

This paper is organized as follows. In section 2, we detail our empirical strategy to describe the determinants of migration. Section 3 presents our integrated assessment model with endogenous migration. We describe the effect of climate change on migration in section 4. Section 5 concludes.

2. Empirical analysis

We carry out an econometric analysis to identify the main economic determinants of migration. We later use the results of the empirical analysis to calibrate our integrated assessment model. That model provides a limited set of variables relevant to migration (income, population by age, past migration flows). The impact of climate change on migration occurs exclusively via damages on economic production. We therefore focus on those variables of interest in our empirical analysis.

2.1. Data description

We use migration data from the International Migrant Stock (2020) dataset, which gives the migrants population in the destination country by origin, sex and age for years 1990, 1995, 2000, 2005, 2010, 2015 and 2020[1]. Our analysis is conducted for the 20 regions defined by the World Population Prospect (WPP)[2]. The first step is to compute the migration flows between countries. Following Abel et al. (2019), we compute the difference of the stock of migrants from country i living in country j between one period and the next. If the stock decreases between two consecutive periods, we obtain a negative value. We thus set migration from country i to country j to zero. We also compute reverse migration, *i.e.*, we count that negative value as a migration flow from country j to country i. This reverse migration is added to the regular migration flow, which is the difference of stock of migrants from country j living in country i between the same dates[3]. Details on the method are given in Appendix A. In a second step, we aggregate migrant flows by region. Migrations within a given region are ignored, leaving out almost 45% of the migrants because they reside in the same aggregate region[4]. With 20 regions, 19 potential destinations for each and the six 5-year periods, we obtain 2280 observations of migration flows. Migrant flows at date t between region i and a destination j (noted $emig_{i,j,t}$) comprise migrants who have arrived between years $t-4$ and t.

We use GDP data from the World Development Indicators (WDI) in purchasing power parity in 2015 international dollars, and population data from the WPP. We regress emigration flows between period t and $t-4$ on GDP per capita and population size of the year $t-5$. We complete our dataset with dyadic variables from the CEPII dataset for gravity models (Head et al., 2010). This dataset was primarily used by Head et al. (2010). We use the weighted distance between two countries, and dummies for the common official language. Bilateral observations are available for 213 countries, but we restrict our dataset to the same 192 countries of the migration data. We aggregate those variables at the regional level, and obtain regional dyadic dummies which are set to 1 if at least one country from the region shares a common language with a country of another region. For the distance between two regions, we use the following method:

1. We compute distance of country i in region A to region B as the minimum of the distances between country i and the countries j in region B: $dist_{i,B} = \min_{j \in B}(dist_{i,j})$
2. The distance between regions A and B is the average of all the distances of countries i in A to region B: $dist_{A,B} = \sum_{i \in A}(dist_{i,B})/N_A$, where N_A is the number of countries in region A.[5]

2.2. Stylized Facts

The impact of our variables of interest – income, population, distances, dyadic variables – is well studied in the literature at the country-level. However, it is more difficult to confirm that the mechanisms

[1]The estimates are based on official statistics on the foreign-born or the foreign population, obtained during census. We focus our analysis on countries that are independent, and for which economic data is available. Our final dataset has 192 countries.

[2]In Appendix A, we describe how countries are aggregated into 20 regions.

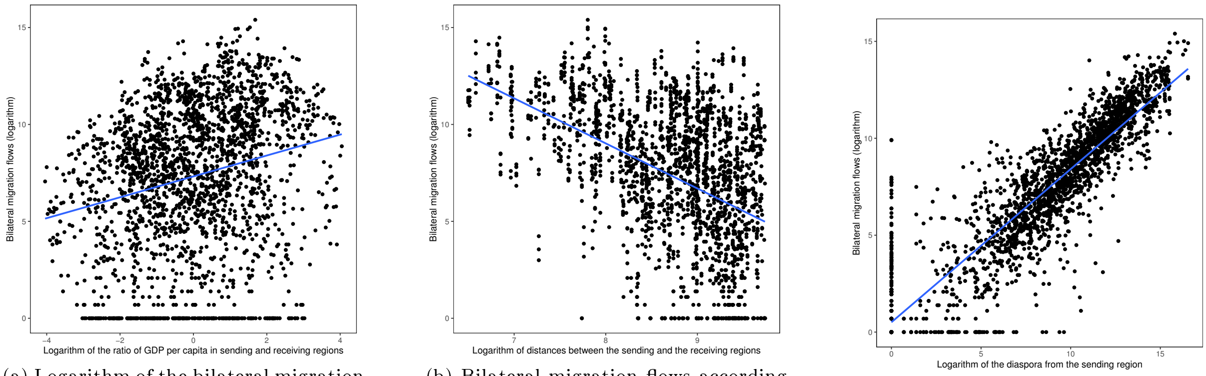
[3]NB: The alternative option is to ignore reverse migration, knowing that negative values can also be due to mortality, given that we are comparing changes in stock (if there is no migration, the stock can still decrease because of mortality), but we do not take that effect into account.

[4]For instance, migration between France and Germany is not accounted for, while migration flows between United Kingdom and France are included.

[5]Distances between countries are weighted by the population densities in the countries, however in the regional aggregation there are not weighted by the population when we take the average.

remain the same (in magnitude) at the regional scale. In this section, we compare the correlations between our potential explanatory variables and our main explained variable at the regional scale. We then display in Figures 1a to 1c the correlations between the bilateral migration flows and our variables of interest.

Figure 1: Bilateral migration flows vs. main explanatory variables



(a) Logarithm of the bilateral migration flows according to the ratio of GDP in logarithm (1990 - 2015)

(b) Bilateral migration flows according to the distance between regions - logarithms (1990 - 2015)

(c) Migration flows vs. diaspora in the receiving region (1990 - 2015)

In Figure 1a, we capture the effect of the difference between incomes in the origin and destination regions, using the logarithm of the ratio of the GDP per capita of the receiving region over that of the sending region. Figure 1a displays a strong positive correlation between this ratio and the bilateral migration flows (in logarithms). This indicates that more than the absolute income in the sending and receiving regions, the important variable is the potential gain from migration, which is captured by the difference of income between both regions. According to the literature, the cost of migration is an important determinant of the choice of destination (Constant and Zimmermann, 2013). This cost can be influenced by distance, network effects and barriers to migration in the receiving region. We expect to observe the same features at the regional level. Figure 1b shows that there is a negative correlation between migration flows and the distance between regions, as expected. Networks or the size of the diaspora in the receiving region may mitigate the cost of migration thanks for instance to information on jobs or administrative barriers (Constant and Zimmermann, 2013). Figure 1c displays a positive correlation between the migrants population in the receiving region and bilateral migration flows at the following period. It is also possible to include the share of foreigners in the receiving regions: countries with a large share of foreigners may have less restrictive migration policies, which might reduce the cost of migration.

Further analysis shows that there is a significant number of null values for migration between regions (9.5% for variable $emig^{ret}_{i,j,t}$). These null values of migration between two regions are often observed over the whole study period (1990-2015). This indicates that the migration corridor between those regions does not exist in any year. We find that this is more likely to happen when migration flows involve Central Asia, Central Africa or Oceania as destination and another developing region as the origin. While at the country scale it is not surprising that some countries never interact with each other through migration, it is more surprising that this occurs here despite the aggregation in large regions.

In line with those stylized facts, we incorporate the following variables in our econometric analysis: the population in both sending and receiving regions, the ratio of GDP, the distances between regions, the diaspora or the share of foreigners, and the dummy variables described earlier. We give descriptive information for our dependent and main independent variables in Table 1.

Table 1: Characteristics of the dataset

Variables char.	Min	Max	Mean	Std. Dev.
Mig. Flows (millions)	0	4.865	0.060	0.231
Reg. Pop. (millions)	7.722	1,827.847	326.525	435.056
Ratio of GDP	0.02	57.05	3.23	6.34
Distances (kilometers)	664.7	16932.9	7630.3	4207.5
Diaspora (millions)	0	15.401	0.309	1.054

2.3. Econometric analysis

Our benchmark regression specification is a simple gravity model of migration between regions. We first regress a Scaled Ordinary Least Squares (SOLS) model with robust standard errors on a log-linearized equation (see equation (1)). This means that to build our explained variable, we add an arbitrary positive value to the emigration flows ($EMIG_{i,j,t} = \ln(1 + emig_{i,j,t})$).[6] This allows keeping the null values and the statistic information on null flows of migration. We may face an estimation issue because of the occurrence of zero values for the dependent variable, and of the heteroscedasticity which can lead to inconsistent OLS estimates. Approximately 10% of our migration flows observations have a zero value, knowing that heteroscedasticity is corrected with the robust standard errors. Second, we also use the Poisson Pseudo-Maximum Likelihood (PPML) estimator developed by Silva and Tenreyro (2006). This method can deal with over-dispersed Poisson distribution, and thus is a good candidate to estimate our model. The PPML estimator is designed to take into account fixed effects, and estimate model with count data as dependent variable. In that case, we directly use the number of migrants and the logarithms of the independent variables into our regression equation. Finally, we also regress (1) with the OLS estimators for comparison.

$$EMIG_{i,j,t} = Constant + \beta_1 \ln(pop_{i,t-5}) + \beta_2 \ln(pop_{j,t-5}) + \beta_3 \ln\left(\frac{gdppc_{i,t-5}}{gdppc_{j,t-5}}\right) + \beta_4 \ln(diasp.i,j,t$$

$$+ \beta_5 \ln(dist_{i,j}) + \beta_6\, com.lang_{i,j} + \beta_7\, colony_{i,j} + \beta_8\, SIDS_i$$

$$+ \beta_I + \beta_J + \beta_{I,J} + \beta_t + \varepsilon_{i,j,t} \quad (1)$$

In equation (1), subscripts i and j refer to sending and receiving regions, respectively. Note that we impose $i \neq j$ for the dependent variable. We take the values for the independent variables of the year preceding the 5 year period of migration flows. The variables *pop*, *gdppc*, *diasp*, *dist* and *com.lang* stand respectively for population size, GDP per capita, diaspora, distances and common official language between regions i and j. We include a dummy $SIDS_i$, which takes the value 1 if the sending region is the Oceania or the Caribbean, which are regions with only Small Island Developing States (SIDS). We also introduce a dummy, which takes the value 1 if the sending region sends refugees among the migrants ($Ref.sender_i$). The idea is to isolate the share of forced migration in migration flows. All variables are transformed into logarithms, except for the dummies. Besides the explanatory variables described earlier, we control for any time-constant source of region heterogeneity by using regional fixed effects after having further aggregated the regions in seven groups: High income regions (Australia and New Zealand, Northern America, Northern Europe, Southern Europe and Western Europe), Latin America and the Caribbean (Caribbean, Central America, South America), Central Eurasia (Central Asia and Eastern

[6]This method was first applied by Wang and Winters (1992).

Table 2: Comparison across regression methods

	SOLS	OLS	PPML
(Intercept)	-4.3756***	-3.4836**	1.4512
	(1.2392)	(1.1730)	(1.2625)
Pop. in sending reg.	0.1886***	0.2538***	0.1511***
	(0.0521)	(0.0466)	(0.0458)
Pop. in receiving reg.	0.4166***	0.3489***	0.1252**
	(0.0358)	(0.0370)	(0.0420)
Diaspora	0.6163***	0.5412***	0.5961***
	(0.0211)	(0.0232)	(0.0255)
Ratio of GDP	0.2651***	0.2743***	0.3462***
	(0.0493)	(0.0542)	(0.0543)
Weighted distances	-0.5272***	-0.5208***	-0.4517***
	(0.0609)	(0.0556)	(0.0496)
Common off. language	0.5244***	0.6023***	0.6590***
	(0.1188)	(0.1190)	(0.1455)
SIDS	-0.4948**	-0.4713**	-0.8589***
	(0.1776)	(0.1821)	(0.1859)
Sends refugees	0.2532**	0.1845*	-0.0605
	(0.0892)	(0.0863)	(0.0997)
Time Fixed effects	YES	YES	YES
Large region Fixed effects	YES	YES	YES
Interaction large region FE	YES	YES	YES
Num.Obs.	2280	2066	2280
R2	0.849	0.810	
R2 Adj.	0.845	0.804	
F			57.965
Std.Errors	HC2	HC2	

Standard errors in parentheses

$^{+}$ significant at $p < .10$; $^{*}p < .05$; $^{**}p < .01$; $^{***}p < .001$

Europe), Sub-Saharan Africa (Eastern Africa, Middle Africa, Western Africa), Other Africa (Northern Africa and Southern Africa), East Asia and Pacific (Eastern Asia, South-Eastern Asia, Oceania), South and Western Asia. Those fixed effects are denoted β_I, β_J and $\beta_{I,J}$, where the subscripts I and J refer to the group of the sending region and that of the receiving region, respectively. We also control for phenomena common to all countries across time through the introduction of time dummies β_t.

Results for the different specifications are described in Table 2. Specifically, column (1) shows results for our benchmark model, the SOLS. Column (2) shows results for the OlS, and column (3) shows results for the PPML estimation.

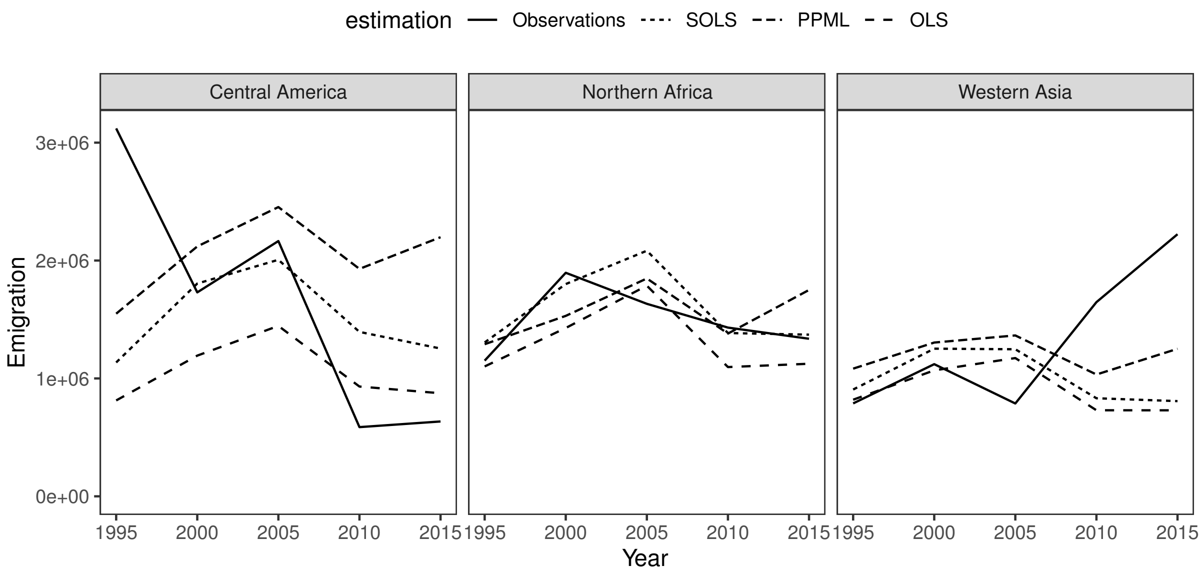
The results are robust and significant for most of our independent variables in all regressions. We find a significant positive correlation between the migration flows and the ratio of GDP per capita, the population sizes in sending and receiving regions as well as the diaspora. We find a significant negative correlation between distances and migration flows. When we compare the different estimations, it appears that coefficients are quite robust. Nonetheless, we find some differences across methods. For instance, we find larger effects for distances in the OLS (scaled or not) that in the PPML (-0.52 for OLS and SOLS vs. -0.45 for the PPML). We find larger effects in the OLS for the population sizes in the receiving region (0.42 and 0.35 for the SOLS and the OLS, respectively, vs. 0.13 for the PPML). On the contrary, effects are smaller in SOLS and OLS for the ratio of GDP per capita (0.27 vs. 0.35) and for the SIDS characteristics (-0.49 or -0.47 vs. 0.86). Also, in the PPML regression, results are not significant for the constant and the refugees, while there are significant and quite large in the SOLS and OLS regressions.

We find very robust results for the effects that we scrutinize and which are the most susceptible to climate change. Indeed, we find almost the same coefficient for the ratio of GDP per capita and the diaspora across methods. We find that an increase of 1% of the migrant stock from a given region leads to an increase of 0.6% in migration flows from that region.

A direct comparison between our estimates and the empirical results from the literature is difficult. As explained in section 1, variations in method, data and scale lead to significant differences. In this work, we capture the elasticity of long distance inter-regional migration flows with respect to our determinants, and at a specific scale which has not been studied in the literature. Nonetheless, we obtain the results we expected for the potential gain from migration (a positive coefficient for the ratio of GDP per capita), the network effect (captured by the positive coefficient for the diaspora) and the distance (a negative coefficient). Our results are robust to changes of specification.

Our main objective is to obtain tractable results that can be used in our stylized integrated assessment model. Despite the simplicity of our econometric method, we obtain quite convincing results for the determinants of migration. This is illustrated by the figures below, which show the ability of the coefficients to reproduce historical data. Figure 2 displays the predicted and observed emigration flows, *i.e.*, the sum of bilateral migration flows by sending region, for Central America, Northern Africa and Western Asia. In Figure 3, we represent immigration flows – the sum of bilateral migration flows by receiving region – for Northern America, Southern Europe and Western Europe, which we use as illustrations for the receiving regions.[7] We then compare the predictions of our model with observations at both the regional and global scales. Observations are displayed in solid lines. Dotted lines show the results for the SOLS model, while the PPML and OLS results are represented in short-dashed and long-dashed lines, respectively.

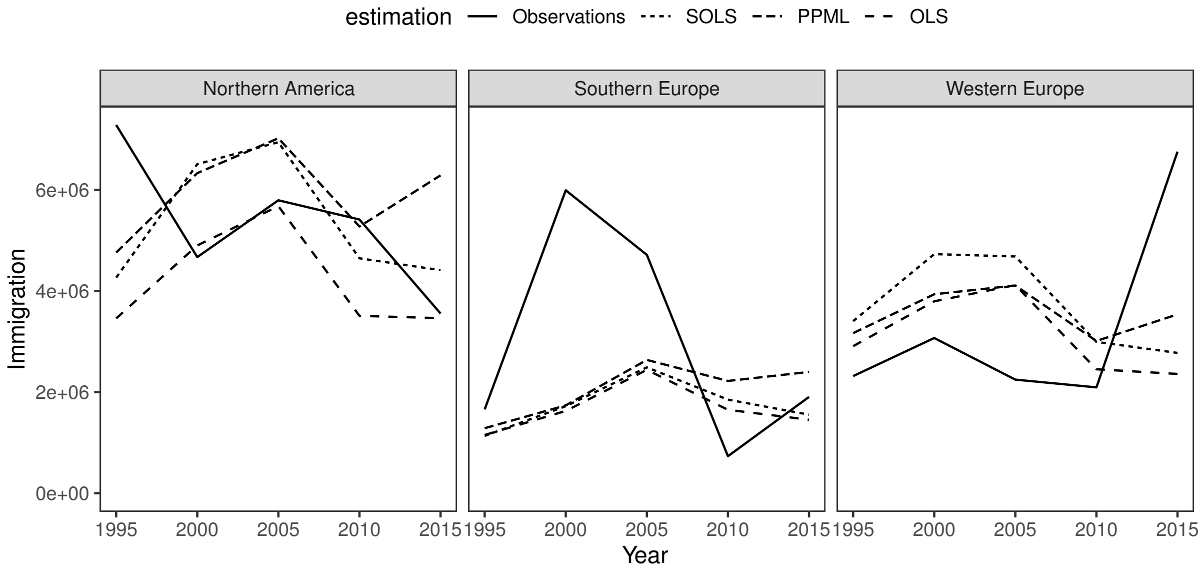
Figure 2: Emigration flows



In our selected regions, all models seem accurate. In Figures 2 and 3, it appears that abrupt changes in migration flows cannot be easily captured by the models. However, it is not a problem for our analysis, which aims at measuring the long-term economic determinants of migration. Note that the divergence between the observations and the predicted values can be explained by the volatility of the migration

[7] In Appendix B, we display the fitted values for all regions.

Figure 3: Immigration flows



flows. In this stylized specification, this is captured by the fixed-effects for the time and the aggregate regions, and it appears that the correction induced by those fixed effects is imperfect.

3. Introducing PRICE: an integrated assessment model with endogenous population dynamics

We introduce the PRICE model, a cost-benefit analysis integrated assessment model based on the RICE model (Nordhaus and Yang, 1996). We modify RICE to include the effect of climate change on migration flows. The model also includes the impact of climate change on mortality, as presented in Pottier et al. (2021). We also introduce several additional damage functions, which were absent from the original RICE specification.

3.1. Population dynamics

In this section, we describe how we model migration dynamics.[8] As a first step, we compute the number of individuals who migrate from region i to region j according to the economic and the demographic determinants of both sending and receiving regions:

$$\begin{aligned} emig_{i,j,t} = exp(Constant) \times pop_{i,t-5}^{\beta_1} \times pop_{j,t-5}^{\beta_2} \times \left(\frac{gdppc_{j,t-5}}{gdppc_{i,t-5}}\right)^{\beta_3} \\ \times dist_{i,j}^{\beta_4} \times \exp(\beta_5 \times contiguity_{i,j}) \times \exp(\beta_6 \times comm.lang_{i,j}) \times \exp(\beta_7 \times colony_{i,j}) \\ \times \exp(\beta_8 \times SIDS_i) \times diaspora_{i,j,t-5}^{\beta_{10}} \times exp(\beta_I) \times exp(\beta_J) \times exp(\beta_{I,J}) \end{aligned} \quad (2)$$

where β_n with $n \in [1, 10]$ are the coefficients obtained in the empirical analysis. As in equation (1), variables *pop*, *gdppc*, *dist*, *diaspora*, *com.lang* and *colony* stand for population size, GDP per capita,

[8]Following Pottier et al. (2021), we model the mortality induced by the temperature increase. This is described in Appendix C.

distance, diaspora, common official language and past or present colonial link between regions i and j. We have $SIDS_i = 1$ if the sending region is the Oceania or the Caribbean. Regional fixed effects by aggregated regions (seven groups) are denoted by β_I, β_J and $\beta_{I,J}$, where I and J refer to the group of the sending and receiving regions, respectively.

We then allocate those emigrants by sex and age in the receiving regions. To do so, we use the United Nations and Social Affairs (2020) dataset, which gives the migrant population by age and sex in each receiving country or region. We assume that the migrant population structure is constant over time. We take the long-term average of the time specific weight of each subpopulation (by age and sex) in the total immigrant population, denoted $W_{x,s,j,t}$ with $t \in [1990, 2020]$.

$$W_{x,s,j,t} = \frac{Migrants_{j,s,x,t}}{\sum_x Migrants_{j,s,x,t}} \tag{3}$$

$$W_{x,s,j} = \frac{\sum_t W_{x,s,j,t}}{7} \tag{4}$$

$$immig_{x,s,i,j,t} = W_{x,s,j} \times emig_{i,j,t} = emig_{x,s,i,j,t} \tag{5}$$

with i the sending region, j the receiving one, x the age group and where $Migrants$ denotes the number of migrants in the receiving region. The variable $immig_{x,s,i,j,t}$ ($emig_{x,s,i,j,t}$) gives the number of immigrants received (emigrants sent) at period t according to their age, sex, origin and destination. By simply summing $immig_{x,s,i,j,t}$ ($emig_{x,s,i,j,t}$) for the 19 potential origins (destinations), we obtain the number of immigrants (emigrants) of a certain age group and sex. At the following period, we consider that immigrants have the same fertility and mortality rates than the natives of their age and sex in their region of residence.

In the baseline scenario, in the absence of climate change damages, we use the WPP projections for fertility and mortality. Migration is endogenous and depends on our econometric results. Our population estimates are thus specific to our analysis. We compare our baseline projections to the medium variant of the WPP estimates for the population to check that we obtain the correct order of magnitude for our population projections without accounting for climate damages.[9] We use the SSP2 "Middle of the Road" baseline scenario from the Shared Socio-economic Pathways to compute the GDP evolution until 2100. That scenario does not account for climate change damages (Fricko et al., 2017).

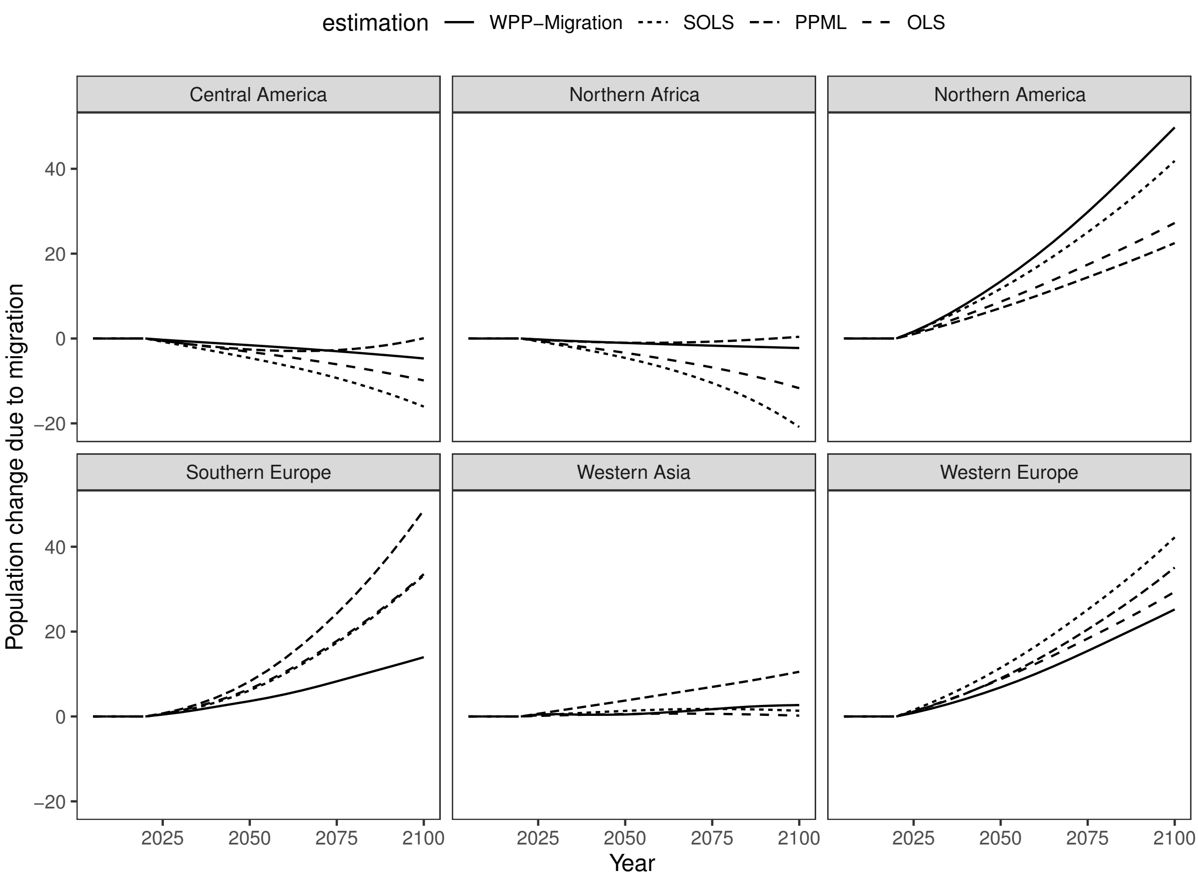
Figure 4 displays the percentage change in population size due to migration with and without migration, in the PRICE model and in the WPP scenario. Without migration, population in the PRICE model and in the zero-migration scenario of the WPP are the same. If our migration estimates are close to the migration estimates, which are included in the medium variant of the WPP, we should observe the same changes in population size in both models. However, comparisons with the WPP projections should be interpreted with care because there are large differences between the WPP methodology and our own. While we implement population displacements that depend on economic determinants, WPP projections rely on probabilistic methods that reproduce past demographic trajectories. We therefore do not expect a perfect replication of their data.

In Figure 4, we present the results for our six regions of interest (results for all regions are shown in Appendix C). First, our projected migration flows have the expected positive (negative) effect on population size for the large receiving (sending) regions. Indeed, accounting for migration dynamics leads to an increase in population size in Northern America, Southern Europe and Western Europe

[9] For details, see the WPP definitions of their population variants.

because net migration is positive in those regions, while we have a negative effect from migration in the other regions (null for Western Asia). This is true for all sets of estimators. Second, we tend to overestimate immigration flows in European regions and emigration flows in Northern Africa or Central America. For instance, by the end of the century, compared to the scenario without migrants, we model an increase of the population in the migration scenario with the SOLS (PPML) estimators of 40% (25%) in Western Europe, while the WPP finds an increase of 23%. For other regions, our findings are very similar to WPP projections.

Figure 4: Projections of population in selected regions



3.2. Climate change damages

The last important component of our analysis is the climate damage function. Our migration projections depend solely on income effects and on the endogenous diaspora. Therefore, the impact of climate change on income is central. We compare population dynamics across three scenarios. The first one – denoted *Nordhaus* – is also the most optimistic one, with a relatively small loss of income due to climate change damages. The damage function is calibrated on coefficients in line with Nordhaus (2018b) results (note our regions differs from those in the RICE model) showing that a temperature increase of 3°C compared to the preindustrial level may induce a 2.1% loss in global income (see Nordhaus and Moffat (2017) for details on the method).

Our second damage function – denoted *Kalkuhl & Wenz* – is calibrated on the results from Kalkuhl and Wenz (2020), where a dataset of subnational economic output for more than 1500 regions in 77 countries is used to regress historical climate impacts[10]. Thanks to their spatially and temporally highly resolved dataset, the authors can differentiate between short-term weather shocks and long-term climatic changes. By differentiating regions according to their average temperature, they find that hot regions are more strongly affected by further warming than cooler regions. In their preferred model with panel analysis, they find a reduction of 14.2% of GDP per capita at 3.2°C warming.

Finally, our third scenario – denoted *Burke & al.* – relies on the estimates of Burke et al. (2015), and more specifically the results of their preferred model, the Pooled Short Rate (PSR) regression. Using a dataset of 166 countries over the period 1960-2010, the authors find that a temperature increase of 5°C may induce a loss of 24% in global income. However, there is a significant heterogeneity in the damage levels, with a 65% increase in GDP per capita for European regions, while Sub-Saharan African regions may experiment a loss of 85% of their income.

Our damage function takes the functional form of Nordhaus (2018b), and parameters Ψ_1^d and Ψ_2^d – coefficients for the linear and the quadratic terms, respectively – are calibrated using the different damages projections with respect to temperature increase described in Nordhaus (2018b), Kalkuhl and Wenz (2020) and Burke et al. (2015).

$$D^d(t) = \Psi_1^d T_{AT}(t) + \Psi_2^d [T_{AT}(t)]^2 \tag{6}$$

where $d \in [1,3]$ denotes the scenario, $D^d(t)$ is the share of climate loss (as % of GDP) and $T_{AT}(t)$ the atmosphere temperature at date t.

Table 3 gives the loss of income for each damage scenario in our 6 regions of interest. Our damage scenarios are very different, both in terms of the magnitude and distribution of damages across regions. However, two elements are similar. The first one is the relatively low impact of climate change on European regions. The second one is the relatively high impact of climate change on Central America and Western Asia. The main difference between the estimates by Kalkuhl and Wenz (2020) and Burke et al. (2015) is observed for Northern America. In the former, that region is among the most impacted by climate change with a loss of 10.4% in GDP per capita for an increase of 3°C compared to the pre-industrial period. In Burke's estimates, Northern America is among the least impacted regions with an income loss of 1.8% in GDP per capita for the same temperature increase.

4. Results

In this section, we discuss the impact of climate change damages on migration projections until 2100. Our estimates are by construction relatively small. This is because we neglect within region migrations that account for 45% of the migration flows, and only account for the most costly form of migration, which occurs across long distances between main world regions. Also, we present here the variations between our baseline scenario and the scenario with climate change, not the absolute values.

Figure 5 shows the change in immigration flows with respect to a hypothetical case without climate damages. We present results for the World, Northern America, Southern Europe and Western Europe, in the three damages scenarios, and according to each set of estimators. The *Nordhaus* scenario is represented with a solid line, the *Kalkuhl & Wenz* scenario is represented with a dotted line, while the

[10] Note that those estimates exclude non-market damages and impacts from extreme weather events or sea-level rise. This is in line with our damage specification.

Table 3: GDP per capita loss (in %) for an increase of 3°C compared to the pre-industrial period.

Scenario	Nordhaus (2018b)	Kalkuhl and Wenz (2020)	Burke et al. (2015)
World	2.8	9.3	24.0
High receiving reg.			
Northern America	1.6	10.4	1.8
Southern Europe	1.9	8.0	-28.8
Western Europe	1.9	4.8	-29.6
High sending reg.			
Central America	2.7	8.7	32.3
Northern Africa	2.7	9.2	31.6
Western Asia	3.1	9.7	31.6

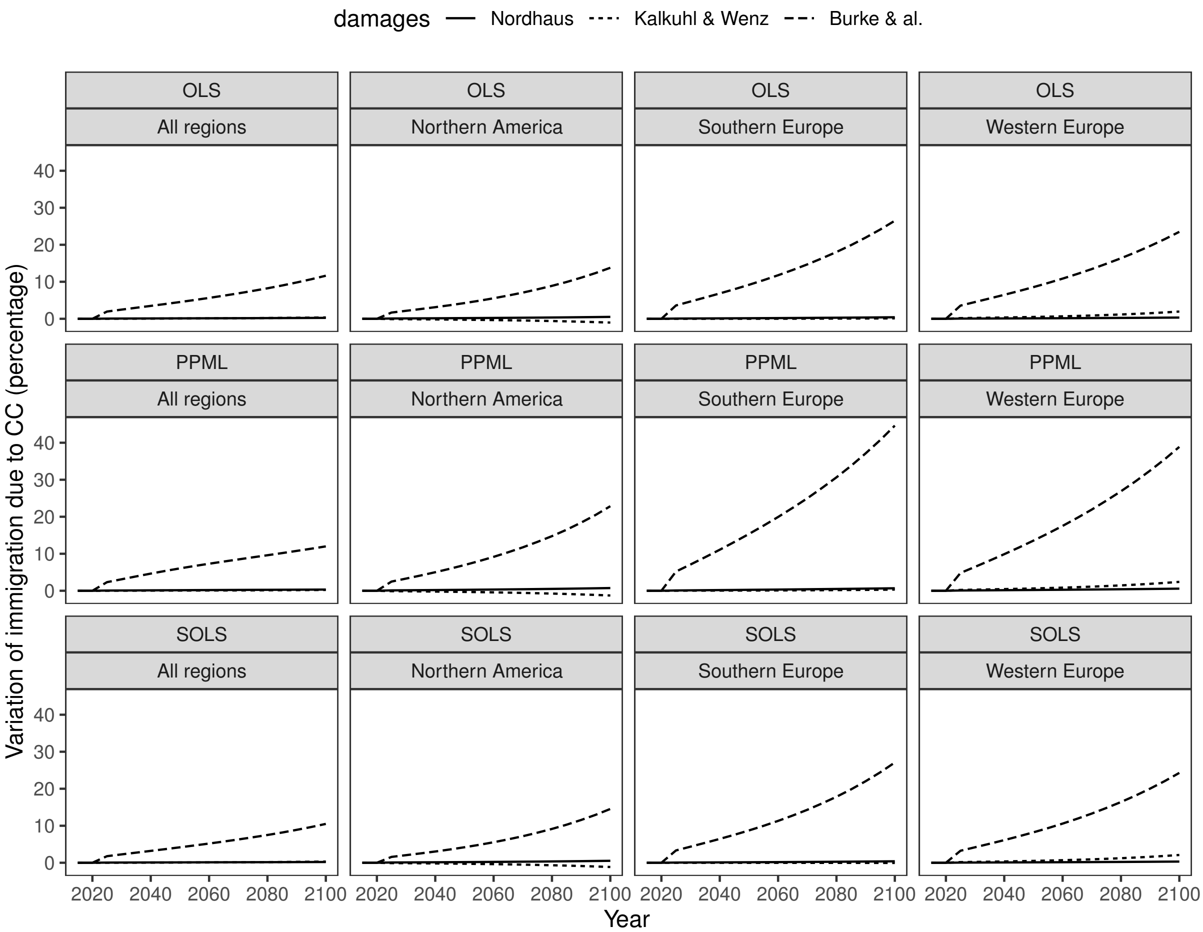
Burke & al. scenario is represented with a dashed line. We focus our analysis on those three regions for immigration because they illustrate well the effect of the heterogeneity of damages on population dynamics. Those regions receive the largest number of migrants for almost all the period 2005-2100, in the three scenarios[11].

At the global scale, we find that migration flows increase because of climate change. However, the magnitude is very different according to the scenario. In the *Nordhaus* and *Kalkuhl & Wenz* scenarios, we find an increase of only 0.3 to 0.6% by the end of the century compared to the baseline scenario without climate change damages. By contrast, in the *Burke & al.* scenario, migration flows are almost 10% higher than in the baseline. This result is quite robust to a change in the regression method. The small increase in migration flows in the *Nordhaus* scenario is quite intuitive. This is due to the fact that economic damages, while non-negligible, remain small compared to those in other scenarios. The rather small increase in migration in the scenario based on Kalkuhl and Wenz (2020) could seem surprising at first. Indeed, in that scenario, climate damages lead to a reduction in GDP per capita of 12.1% at the end of the century. However, climate induced migration is limited because of the heterogeneity in damages. A rise in migration flows due to climate change can be observed if the difference in income across regions increases, and if the cost of migration is not too high, *i.e.*, if regions are relatively close, and if the diaspora is large enough. We do not observe strong changes in migration flows at the global scale, even in the *Kalkuhl & Wenz* scenario where the global income losses are relatively high. However, results may differ at the regional scale. We analyze in more details the migration flows towards Northern America and Western Europe in Figure 6, which displays the climate induced variations in emigration flows in Central America, Northern Africa and Western Asia.

In the *Kalkuhl & Wenz* scenario, immigration in Northern America decreases slightly, while we observe a reduction in emigration flows from Central America, which is one of the main sender of migrants to Northern America. In that same scenario, damages in Northern America are higher than in Central America (respectively 10.4% and 8.7% for 3°C, *cf.* Table 3). Climate change damages thus reduce the relative gain of migration for the traditional senders of immigrants to Northern America, which are the

[11] In the observations of migration flows between 1995 and 2015, for some years, the number of immigrants in Western Asia is higher than in Western Europe. However, there is a higher volatility in the stocks of migrants in Western Asia than in Western Europe.

Figure 5: Change in the immigrants flows due to climate change damages according to the scenario

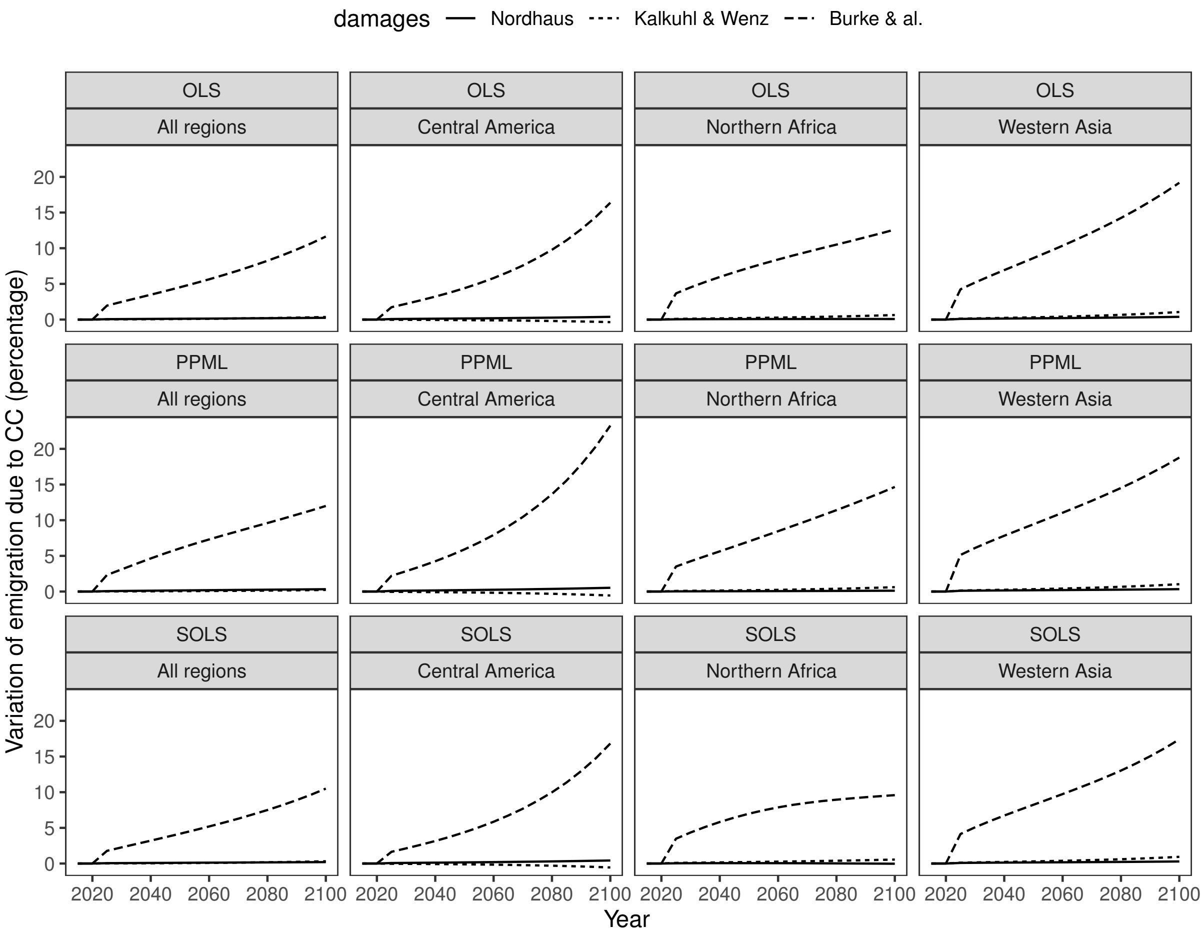


Caribbean, Central America, and South America. Still in the *Kalkuhl & Wenz* scenario, Northern Africa and Western Asia lose 9.2 and 9.7% respectively, while in Southern Europe and Western Europe, damages are equal to 8.0%, and 4.8% in Western Europe. In this case, damages are higher in traditional net sending regions, which leads to an increase in migration flows between those regions (although the heterogeneity in damages is limited). This results in an increase of migrations flows by 2% in Western Europe (the least impacted region), the highest variation in migration flows we find among the 20 regions. Damages are large in Southern Europe, and immigration flows decrease. Again, this result is robust to changes in the regression method.

In the *Burke & al.* scenario, the regional heterogeneity of damages is so high that we observe a strong increase in migration flows at both global and regional scales. This is in part due to the distribution of damages among regions. Indeed, the more impacted regions are also those with larger emigration flows. Traditional receiving regions in Europe are even benefiting from climate change, while damages are limited to a loss of 1.8% of GDP per capita towards the end of the century in Northern America. By comparison, income decreases by 32.3% in Central America compared to the baseline, which explains the rise of almost 18% (25%) of the migration flows toward Northern America with the SOLS (PPML) estimators.

To analyze the impact of climate change damages on the composition of migration flows in 2100 in the *Burke & al.* scenario, we represent migration flows (in thousands) by origin and destination at

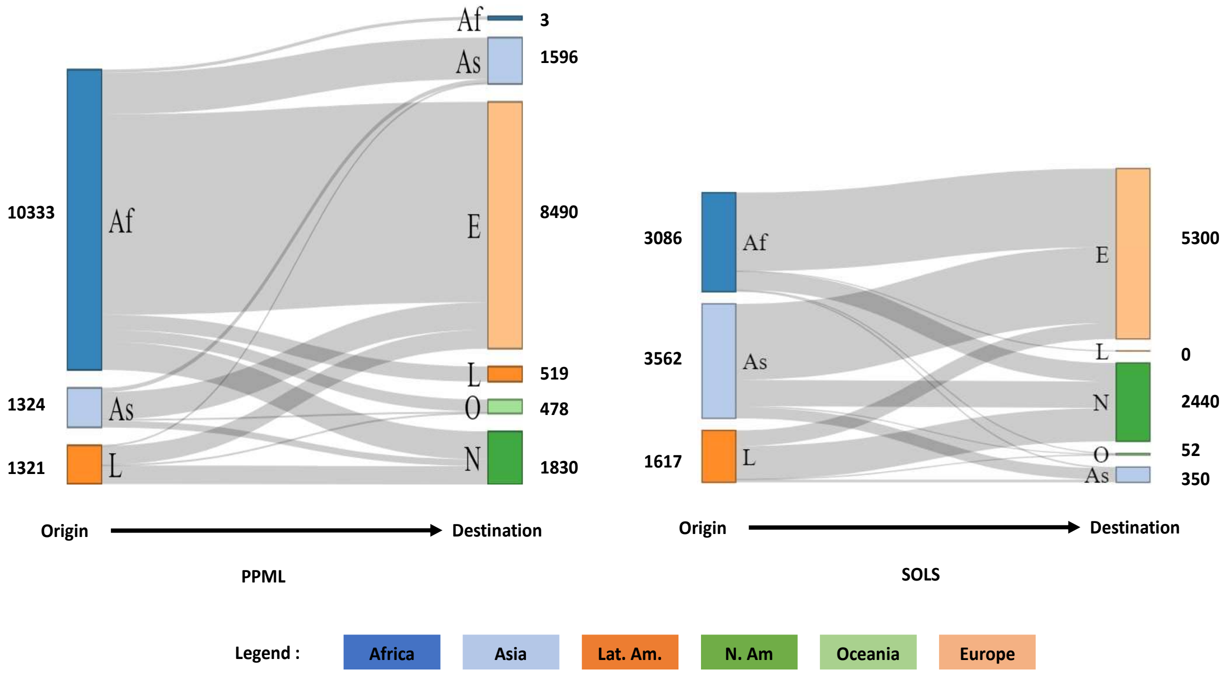
Figure 6: Change in the emigrants flows due to climate change damages according to the scenario



the continental level (Figure 7). We show the number of climate-related migrants by continent with the PPML (left) and SOLS (right) specifications. Figure 7 shows that due to the proximity of African regions and Asian regions, European regions are more likely to receive climate migrants than Northern America. Indeed, almost 8.5 (5.3) millions of climate-related migrants arrive in European regions with the PPML (SOLS) regressors, while there are 1.8 (2.4) millions of climate-related migrants in Northern America with the PPML (SOLS) regression. The main sending regions are in Africa and Asia. However, we can see that the method here has a significant effect on the projections of climate-related migrant flows. Therefore, while it is quite certain that Europe will receive most of climate-related migrants, their origin remains uncertain.

Lastly, we examine the relationship between global income and migration. Migration may impact global income and vulnerability to climate change, as more individuals end up in wealthier, colder regions. In the absence of migration, global GDP per capita is reduced by 24.9% in 2100 compared to baseline in the *Burke & al.* scenario, while the loss is only 20.8% (20.9%) with migration projected with the PPML (SOLS) estimators. Migration may reduce global income losses due to climate change, via two mechanisms. Because of climate change, people in vulnerable regions are incited to migrate to less exposed areas. Thus, they benefit from a higher income than in their region of origin, and make the global population wealthier. We compare the change in global GDP per capita and in global income with and without migration in the baseline scenario. In the absence of climate change damages, if migration

Figure 7: Climate related migration flows in *Burke & al.* scenario by origin and destination continents (thousands)



is not possible, global GDP per capita decreases by 5.8% (4.3%) in 2100 compared to the scenario with migration computed with the PPML (SOLS) estimators. We can interpret this difference as the result of the displacement of the population to regions where incomes are higher, independently of the distribution of climate change damages. In the *Burke & al.* scenario in the absence of migration, global income is reduced by 10.7% with the PPML model (9% with the SOLS model) in 2100 compared to the global income when migration in permitted. Therefore, the increase in migration has led to a larger displacement of the population towards wealthier regions, which are also less exposed to climate change.

5. Conclusion

In this paper, we study the impact of the heterogeneity of future climate impacts on climate change-related migration. We estimate a gravity model, and include that estimation in an integrated assessment model to represent endogenous migration flows. The main drivers of (international) migrations that we account for are differences in GDP per capita in sending and receiving regions and the size of the diasporas. Climate change may have an ambiguous effect on migration as it acts both as a push and pull factor, depending on the distribution of damages across regions.

We highlight that the shape and regional distribution of climate damages are crucial to know whether climate change may trigger large migration flows. With traditional damage functions (Nordhaus, 2018b), we find very limited excess migration. On the contrary, with some of the more recent estimates (Burke et al., 2015), the excess migration flows can be up to 30% compared to baseline projections without climate damages. There are also many specific differences at the regional level depending on the regional distribution of damages: some regions may or may not experience large immigration flows depending on their own damages and those of the neighboring regions. Our main conclusion is that it is crucial to better understand the spatial heterogeneity of climate damages in order to draw conclusions on future migration flows.

One limitation of our global model is that it only represents international migrations at the level of rather aggregate regions. We cannot draw conclusions on future migration flow at the infra-regional level, while it is known that most of the migrations occur at that level. Increasing the spatial resolution of the model (at the country level for instance) would raise econometric challenges in the estimation of the model, given the large number of country fixed effects. This interesting line of research is left for future work.

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Appendix A. Data description

The migration flows are computed according to the following computation:

$$\begin{cases} emig_{o,d,t} &= stock_{o,d,t} - stock_{o,d,t-5} \\ & \quad \text{if } stock_{o,d,t} > stock_{o,d,t-5} \& stock_{d,o,t} > stock_{d,o,t-5} \\ emig_{o,d,t} &= 0 \text{ if } stock_{o,d,t} < stock_{o,d,t-5} \& stock_{d,o,t} > stock_{d,o,t-5} \\ emig_{o,d,t} &= -(stock_{d,o,t} - stock_{d,o,t-5}) \\ & \quad \text{if } stock_{d,o,t} < stock_{d,o,t-5} \& stock_{o,d,t} < stock_{o,d,t-5} \\ emig_{o,d,t} &= -(stock_{d,o,t} - stock_{d,o,t-5}) + (stock_{o,d,t} - stock_{o,d,t-5}) \\ & \quad \text{if } stock_{d,o,t} < stock_{d,o,t-5} \& stock_{o,d,t} > stock_{o,d,t-5} \end{cases} \tag{A.1}$$

In equation (A.1), at the date t, $emig_{o,d,t}$ is the migration flows with return migration between a country of origin o and a country of destination d; $stock_{o,d,t}$ is the stock of migrants from a country o residing in the country d. The second step is to sum these bilateral migration flows by region of origin and region of destination, knowing that migration flows between countries which are in the same region are not taken into account.

Table A.4 gives the list of countries included in our analysis by region.

Table A.4: Included countries by regions

Code	Region	Countries
1	Australia and New Zealand	
2	Caribbean	Anguilla, Antigua and Barbuda, Aruba, Bahamas, Barbados, British Virgin Islands, Cayman Islands, Dominica, Dominican Republic, Grenada, Haiti, Jamaica, Montserrat, Puerto Rico, Saint Kitts and Nevis, Saint Lucia, Saint Vincent and the Grenadines, Trinidad and Tobago, Turks and Caicos Islands
3	Central America	Belize, Costa Rica, El Salvador, Guatemala, Honduras, Mexico, Nicaragua, Panama
4	Central Asia	Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, Uzbekistan
5	Eastern Africa	Burundi, Comoros, Djibouti, Ethiopia, Kenya, Madagascar, Malawi, Mauritius, Mozambique, Rwanda, Seychelles, Uganda, United Republic of Tanzania, Zambia, Zimbabwe
6	Eastern Asia	China, China Hong Kong SAR, China Macao SAR, Japan, Mongolia, Republic of Korea
7	Eastern Europe	Belarus, Bulgaria, Czechia, Hungary, Poland, Republic of Moldova, Romania, Russian Federation, Slovakia, Ukraine
8	Middle Africa	Angola, Cameroon, Central African Republic, Chad, Congo, Democratic Republic of the Congo, Equatorial Guinea, Gabon, Sao Tome and Principe
9	Northern Africa	Algeria, Egypt, Libya, Morocco, Sudan, Tunisia
10	Northern America	Bermuda, Canada, United States of America
11	Northern Europe	Denmark, Estonia, Finland, Iceland, Ireland, Latvia, Lithuania, Norway, Sweden, United Kingdom
12	Oceania	Fiji, Kiribati, Marshall Islands, Micronesia (Fed. States of), Papua New Guinea, Samoa, Solomon Islands, Tonga, Tuvalu, Vanuatu
13	South America	Argentina, Bolivia, Brazil, Chile, Colombia, Ecuador, Guyana, Paraguay, Peru, Suriname, Uruguay, Venezuela
14	South-eastern Asia	Brunei Darussalam, Cambodia, Indonesia, Lao People's Democratic Republic, Malaysia, Myanmar, Philippines, Singapore, Thailand, Viet Nam
15	Southern Africa	Botswana, Eswatini, Lesotho, Namibia, South Africa
16	Southern Asia	Bangladesh, Bhutan, India, Iran, Maldives, Nepal, Pakistan, Sri Lanka
17	Southern Europe	Albania, Bosnia and Herzegovina, Croatia, Greece, Italy, Malta, Montenegro, North Macedonia, Portugal, Serbia, Slovenia, Spain
18	Western Africa	Benin, Burkina Faso, Cabo Verde, Côte d'Ivoire, Gambia, Ghana, Guinea, Guinea-Bissau, Liberia, Mali, Mauritania, Niger, Nigeria, Senegal, Sierra Leone, Togo
19	Western Asia	Armenia, Azerbaijan, Bahrain, Cyprus, Georgia, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, State of Palestine, Syrian Arab Republic, Turkey, United Arab Emirates, Yemen
20	Western Europe	Austria, Belgium, France, Germany, Luxembourg, Netherlands, Switzerland

Appendix B. Empirical results - regions

In Figure B.8, we display the regional fitted emigration flows for the regressions (2) to (4) described in Table 2. While in the main sections of this work we have described the results for selected regions and at the global scale, here we display the results for our twenty regions. We compare the observations (represented by solid line) and the fitted values according to the three benchmark models. We observe that at the global scale, the PPML regression is better than the others, however it might overestimates the migration flows for certain regions. On the contrary, fitted values for the SOLS and the OLS regressions are underestimating the migration flows both at the regional and global scales, except for Southern Europe, and Oceania. Moreover, we can see than in Western Asia there is an important increase in emigration flows in the periods 2010-2015 and 2015-2020. However, this important increase is not well captured by the model.

Appendix C. Population dynamics in PRICE

Appendix C.1. Climate-induced Mortality

For mortality and fertility, we use the method described in Pottier et al. (2021), who compute population evolution using the cohort-component method. The authors use data from the WHO (2014) the climate induced health and data from United Nations and Social Affairs (2019) to calibrate the lifetables. In the cohort-component method, population is structured by age and sex. We denote the number of females (males) between age x and $x+5$ at date t by $N^F_{x,r}(t)$ ($N^M_{x,r}(t)$), with r the region. The population is divided into five-year age groups with the oldest group (an open-ended group) with all persons who are 80 years old or more. There are thus 34 groups in our analysis at each date t: $2 \times (16+1)$. With our method, we project the population at date $t+5$ with the same structure after applying the fertility, the mortality and the migration.

We denote the number of births occurring between dates t and $t+5$ by $B_r[t, t+5]$. Thanks to the WPP dataset, we know the number of births by woman according to their age, region of residence, and for each period until 2100, $F_x, r(t)$. Once, we have the number of births, we can also allocate them between male and female population thanks to the sex ratio at birth, which is specific to the region and the period. Finally, we obtain the number of new individuals $N^s_0(t+5)$ of sex s, by applying the survivorship ratio of new born and children from 1 to 4 years old. Projecting the other groups is even more simple, because we simply multiply the survivorship ratio (SVR), by age, sex and region to predict the size of the subpopulation $N^s_{x,r}(t+5) = N^s_{x,r}(t+5) \times SVR^s_{x,r}(t)$.

The climate change related mortality is introduced thanks to the report by the WHO (2014), which gives the additional deaths due to climate change for five mortality risks: undernutrition (for children under 5), malaria (for all ages), diarrhoeal disease (for children under 15), dengue (for all ages) and heat (for people above 65)[12]. The report gives the number of additional deaths for different scenarios in 2030 and 2050. The variations of climate change impact for the next decades are negligible. In the work by Pottier et al. (2021), and by extension in our analysis, we only include a fraction of the mortality associated to climate change, and not for instance emergent viruses, conflicts or extreme events. We compute the increase in the probability of dying for the sex-age-specific subpopulation according to the age specific

[12]They also describe potential flood-related deaths, however no number is given.

Figure B.8: Emigration flows by region - regressions with only positive values

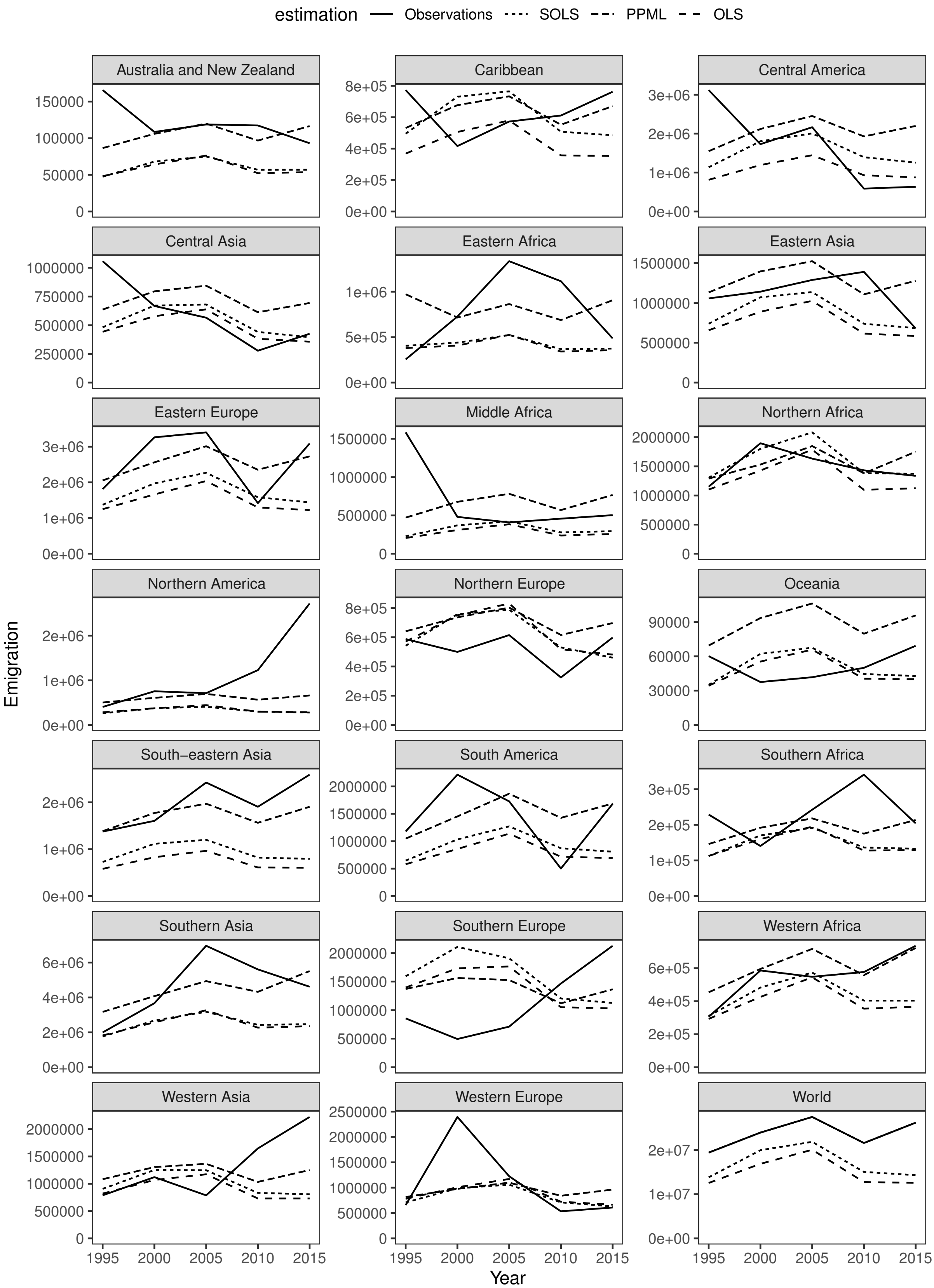
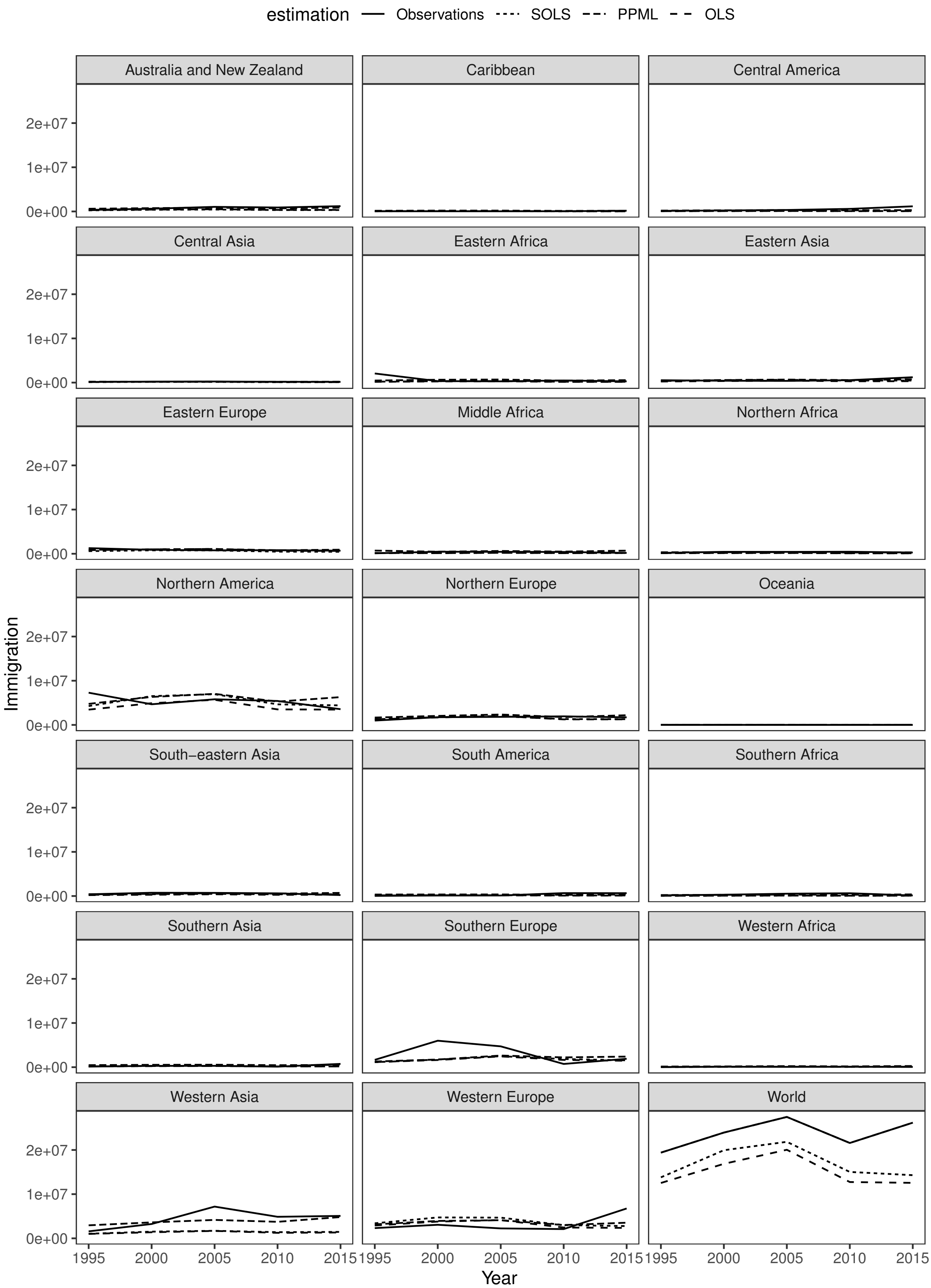


Figure B.9: Immigration flows by region - regressions with only positive values



risks faced by the population. We thus modify the survivorship ratio accordingly to incorporate this increase in the probability of dying.

$$\tilde{q}^{s}_{x,r}(t) = q^{s}_{x,r}(t)\left[1 + \left(\sum_{d \in N(x)} \alpha_d\right) T_t^{\theta}\right] \tag{C.1}$$

where the sum is taken over the five possible mortality risks $d, N(x)$ is the set of risks relevant for the age group between x and $x+5$, T_t is the global temperature increase at time t, α_d is the relative increase in the probability of dying due to risk d at the calibration temperature increase. Parameter θ specifies the dependence of the probability of dying with respect to temperature.[13].

Appendix C.2. Population projections

Figure C.10 displays the population size in our projections compared to the WPP projections for our selected regions, and depending to the migration scenario. Blue lines display population in the scenario without migration, while the scenario with migration are represented by red lines. Projections in our PRICE model are displayed in red lines, and the dotted lines represent the WPP model. With the PRICE model, we project population sizes which are close to WPP projections in our selected regions when migration is not taken into account. When we incorporate migration flows, projections may differ, e.g., in Northern Africa, Southern Europe and Western Europe.

Appendix D. Simulations

Appendix D.1. Supplementary results by regions

In this section, we present the change in migration flows due to climate change damages for all regions as well as the global scale. We display the impact of climate change by region on emigration in Figure D.11, and on immigration on Figure D.12. We display the results for the *Nordhaus* (solid lines), *Kalkuhl & Wenz* (dotted lines), and *Burke & al* (dashed lines) scenarios.

From Figure D.11, it is clear that migration flows are not strongly impacted by the damages in *Nordhaus* or *Kalkuhl & Wenz* scenarios, whether at the global scale or regional level. As explained in section 4, damages are not sufficiently heterogeneous between close regions to induce strong migration flow increases. The only regions where emigration decrease are European regions. This is because the difference in damages with neighboring regions is not large enough to trigger an increase in emigration. On the contrary, Northern America is disproportionately impacted by climate change, and even if it is wealthier than its neighbors, emigration might increase. In the *Burke & al.* scenario, we find large changes in emigration, especially in African regions.

Depending on the regression method used, the regional scale results remain the same, except for African regions. Indeed, in the PPML results, there are some migrants flows between African regions. This is not the case when we use the SOLS regressors. The results are not robust across estimators for those regions.

[13]See Pottier et al. (2021) for a discussion of this functional form

Figure C.10: Population projections by region

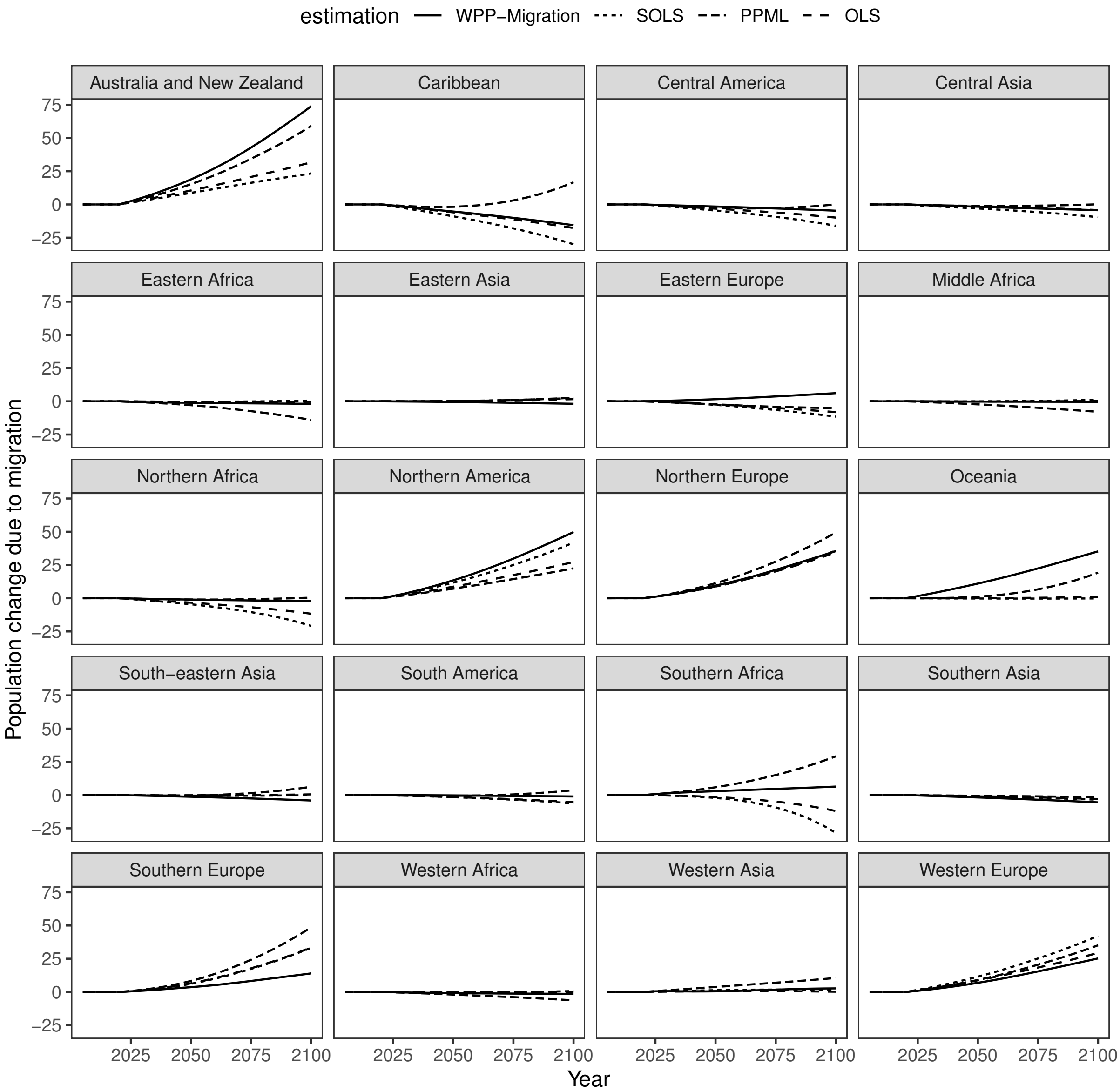


Figure D.11: Change in emigration flows by region

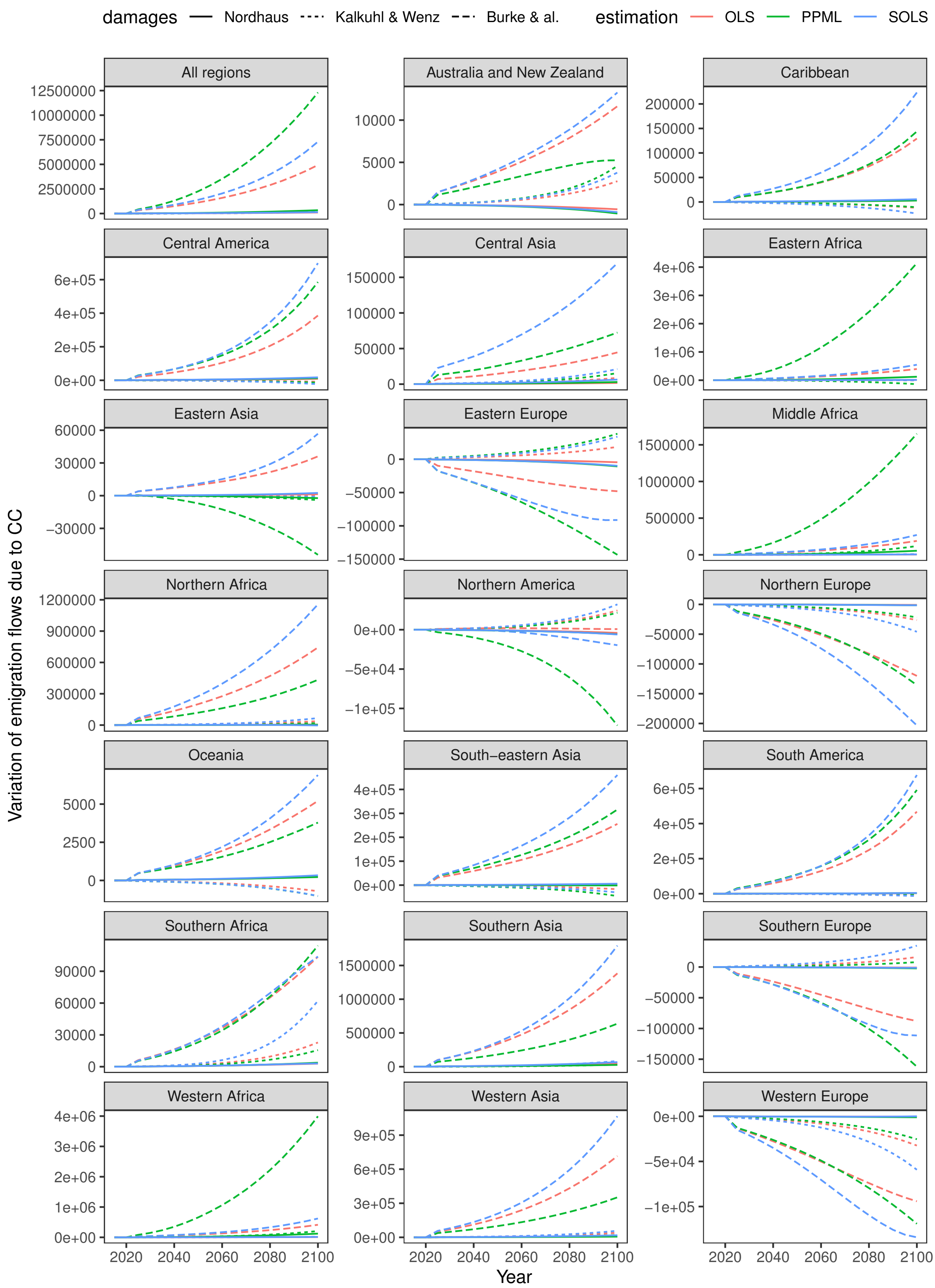


Figure D.12: Change in immigration flows by region