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More people too poor to move: divergent effects of climate change on global migration patterns

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Abstract

The observed temperature increase due to anthropogenic carbon emissions has impacted economies worldwide. National income levels in origin and destination countries influence international migration. Emigration is relatively low not only from high income countries but also from very poor regions, which is explained in current migration theory by credit constraints and lower average education levels, among other reasons. These relationships suggest a potential non-linear, indirect effect of climate change on migration through this indirect channel. Here we explore this effect through a counterfactual analysis using observational data and a simple model of migration. We show that a world without climate change would have seen less migration during the past 30 years, but that this effect is strongly reduced due to inhibited mobility. Our framework suggests that migration within the Global South has been strongly reduced because these countries have seen less economic growth than they would have experienced without climate change. Importantly, climate change has impacted international migration in the richer and poorer parts of the world very differently. In the future, climate change may keep increasing global migration as it slows down countries' transition across the middle-income range associated with the highest emigration rates.

1. Introduction

Earth's surface has warmed by about 1 °C on average since the turn of the 20th century. Impacts of climate change have materialized across the world and pervaded nearly all natural and human-made environments. Climate change has altered the hydrological cycle and the functioning of terrestrial and marine ecosystems; it has affected human health and exposure to natural hazards, agricultural productivity, and various other economic activities [1]. Recent research has indicated that these impacts of global warming have already left an imprint on countries' economic development [2–4]. While neither the magnitude of this effect, nor the relative importance of different sectors and pathways, are fully understood, it is becoming increasingly clear that the global warming of the last decades may have reduced economic

growth in most countries of the world [5–7]. Since growth losses tend to be higher in poorer countries of the Global South than in industrialized countries of the Global North, climate change may have increased economic inequality between countries, on a global level [6].

Since economic conditions in origin and destination countries are among the strongest correlates of international migration [8–10], it seems plausible that these economic changes have also affected migration. But the underlying mechanisms and the magnitude of this effect are not yet understood. Here, we explore this indirect link between recent climate change and international migration, which has to our knowledge not been investigated to date. To this end, we use two recent, alternative approaches to estimating the macroeconomic effects of climate change [7]; a novel historical temperature dataset that includes a

counterfactual scenario without global warming; and a model of international migration that captures the complex dependence of migration on origin and destination countries' income levels.

It has been recognized that emigration rates tend to be highest in middle-income countries, and lower in both, low-income countries and high-income countries. This non-monotonous relationship between average income and emigration—termed the 'migration hump'—has been empirically demonstrated, and theoretically explained as a result of migration aspirations, credit constraints, demographic structure and skill composition of the population, as well as other factors [11–13]; but it is not usually accounted for in models of global migration. We employ a model of global bilateral migration that accounts for the 'migration hump', as well as for other important aspects of the global migration system such as the role of existing migrant networks (diasporas) and the role of return and transit migration [14]. It thus captures the most important processes thought to drive (non-refugee) international migration at a global scale, while being simple enough to calculate simultaneously all bilateral flows globally and thereby accounting for the interdependence of different bilateral links.

We apply this model to three alternative scenarios of country-level gross domestic product per capita (GDPc): one representing the actual GDPc during a recent baseline period (1990–2020); and two scenarios representing GDPc during the same period but for a counterfactual world with no global warming trend since 1900, using two different methods to calculate the effect of historical warming on GDPc. We then compare the resulting migration flows between factual and counterfactuals to gain insight into the potential effects of historical climate change on international migration patterns. Importantly, our approach assumes that the 'migration hump' is reflective of a long-term process—often termed the mobility transition [15]—whereby countries' emigration rates first increase and then decline again as their average incomes gradually rise. This assumption, though in line with other studies [11, 16], cannot be backed up with available global migration flow data [13], and our results are thus conditional on this plausible but untested assumption.

Our study complements existing literature that provides empirical evidence for climate or weather variations influencing migration at different scales. Recent studies have found significant effects of variations in temperature, and sometimes also variations in precipitation or different types of natural disasters, on international migration [17–22] as well as internal migration and urbanization [e.g. 23–25]. Some studies have also provided estimates of the number of people that have migrated in relation to such climatic factors [26]. However, there are hardly any attempts to quantify the number or fraction of migration moves that might be attributable to recent global climate change; with the exception of specific case studies of small island states or coastal communities affected by sea level rise [27].

The empirical studies also rarely allow insight into the mechanisms through which a climatic variable such as temperature affects migration. The few existing studies that explicitly address such mechanisms suggest that indirect effects may be important for international migration in particular, and point to the role of the agricultural sector, being impacted e.g. by drought and heatwaves, and affecting the wider economy and thereby also migration [28–31]. In particular, this mechanism might produce a divergent effect on migration from low- and middle-income countries, pointing to the role of liquidity constraints to migrating [18, 32] and the notion of trapped population [33]. While these studies provide insights on the role of climate factors in driving past migration flows, they mainly focus on specific regions or countries and they do not provide quantitative estimates of the potential changes in migration induced by climate change impacts. Our study explicitly focuses on a single variable known to be an important determinant of migration flows—a country's income level, proxied by GDPc—and estimates the effect that climate change might have had on migration through this variable. While both the migration model and the model of the climate change effect on GDPc are associated with uncertainties and important assumptions that will be discussed below, this focus on a single impact channel makes our approach transparent and compatible with past and future studies aiming to quantify different impact channels of climate change on migration.

2. Methods

In order to estimate the climate change induced international migration flows, we use an international migration model that explicitly depends on GDPc levels at origin and destination. Our central premise is that GDPc would have been different under a counterfactual past without climate change. We estimate GDPc values under this counterfactual past without climate change, and feed them into the migration model, producing counterfactual international migration flows. The difference between these flows and those produced by the same model but using factual GDPc gives a quantification of climate change induced international migration flows.

2.1. Data
Our data covers the period of interest from 1990 to 2020. We use bilateral migrant stocks [34] and total national residents [35] data from the UN. Annual country-level GDPc data comes from the Penn World tables [36, 37]. Bilateral migration flow data comes from a global flow dataset derived from reported

bilateral migrant stocks [38]. Counterfactual temperature comes from a detrended observational dataset where the long-term climate trend was removed but observed variability is preserved [39]. An extensive description of the data is given in the supplementary material, section 1.1.

2.2. Migration model

We use a novel migration model which includes the main drivers of international migration and captures the major processes that depend on them: return migration, diaspora feedback and migration transition [14]. By defining population by place of birth and residence the model captures three types of migration: emigration from the place of birth, transit between countries different from the place of birth, both described by equation (1*a*), and return migration to the country of birth as in equation (1*b*).

$$M_{k,i \to j} = a_j \cdot F(G_i) \, g_j^{\alpha_g} \, p_{k,j}^{\alpha_p} \, P_{k,i}$$

$$\text{for } k \neq j, \tag{1a}$$

$$M_{j,i \to j} = b_i \cdot P_{j,i}, \tag{1b}$$

where $M_{k,i \to j}$ is the migration from country i to country j of people born in country k. The simpler equation describing return flows (equation (1*b*)) is in line with previous empirical estimates that have highlighted the strong proportionality of return flows on the size of the diaspora living abroad [40, 41]. Moreover, other findings suggest that economic drivers have only a limited influence on return flows [42, 43]. a_j and b_i are country-specific scaling factors that could capture the effects of unobserved variables, such as immigration policies. While we acknowledge the fact that there might be different country specific unobserved variables at both origin and destination, for simplicity we decide to keep restricted the number of country specific scaling factors used in the model. Moreover, in order to keep the model dependent on naturally recognizable variables, we implement the country specific scaling factors in a way of capturing predominantly immigration policies. We assume that for emigration from the country of birth and transit migration, both described by equation (1*a*), the factor is specific to the destination country, because these flows are plausibly influenced by immigration policies—and possibly, other factors—in the destination country. For return migration, in equation (1*b*), the factor is specific to the residence country, because e.g. immigration restrictions in the host country may discourage migrants to return to their country of birth [44]; while (entering) immigration policies in country of birth are assumed to not apply to returning nationals. G_i is the GDPc in the country of origin i, and $g_j = G_j / G_{\text{glob}}$ is the GDPc at the country of destination j expressed relative to the global mean GDPc, G_{glob}. The relative diaspora born in k and living in

country j is represented by $p_{k,j} = \frac{P_{k,j}}{\sum_j P_{k,j}}$ and $P_{k,i}$ is the population of place of birth k at risk of migrating from the country of residence i. The function $F(G_i)$ captures a non-linear dependence of emigration on the GDPc of the country of origin:

$$F(G_i) = \frac{1}{1 + \frac{G_i}{\hat{G}}} \cdot \frac{1}{1 + e^{-\gamma(G_i - \bar{G})}}, \tag{2}$$

where $\hat{G}$ and $\bar{G}$ are parameters. The first term is meant to represent the desire to migrate while the second describes the dependence of emigration rates on the economic resources. Their superposition very well matches a non-parametric fit of country-level emigration flows (supplementary material figure S1).

We calculate bilateral migration flows for each five-year interval within the historical period 1990–2020 using the historical GDPc, population, and migrant stocks distributions. In same manner, we produce counterfactual migration flows from each of the two counterfactual GDPc dataset, keeping all other inputs the same as in the factual case. This approach of holding 'all else constant' implies that we neglect any interactions between GDPc and other migration drivers, assuming that GDPc can be adjusted without changing either total population levels or bilateral migrant stocks. In reality, a different evolution of historical GDPc would likely have affected these other variables too. In particular, our premise that GDPc affects migration in a non-linear way already means that as soon as the factual and counterfactual GDPc start deviating, so will migrant stocks. An extended discussion of this topic is included in supplementary material section 2. Here, we note that these effects are of second order compared to the direct effect of GDPc on migration, given that GDPc differences between factual and counterfactual are very small initially, and are overall small enough that their effects on fertility and mortality should be very limited. Thus, adjusting only GDPc while keeping everything else constant is a simple yet acceptable approximation of a more complex, hypothetical experiment which considers all possible interactions.

Other approaches, as generalized linear models, have been used for estimating and making projections of international migration flows [45]. These models do not account explicitly for the economic drivers of international migration, nor for nonlinear processes as are those captured by the 'migration-hump' function. Therefore, these models cannot be used for investigating how international migration would react to changes of the economic drivers. This is a critical limitation when considering that climate change impacts on international migration might act through the indirect pathway of economic impacts.

2.3. Climate change effect on per capita GDP

The climate change effect on country-level economic productivity is captured using two different methods.

In the first case, we employ the cross-sectional regression model of equation (8) in [7]; we refer to this as the '*long-term*' impact case because this method captures potential long-term adaptation of economies to gradual changes in climate. In this model, the logarithm of the average GDPc of a (sub-national) region i at time t is regressed as a linear function of average temperature and average precipitation while accounting for regional covariates with respect to geographical endowment and country fixed effects. We here apply the results to the country level. Neglecting precipitation as it is a non-significant predictor allows us to write the logarithm of average GDPc $G_{t,i}$ of country i at time t as

$$\ln G_{t,i} = \alpha_T T_{t,i} + \ln \tilde{G}_{t,i}. \tag{3}$$

The first term on the right-hand-side of equation (3) describes the impact of average temperature $T_{t,i}$ on GDP with the linear impact coefficient $\alpha_T < 0$ while the second term combining covariates and country fixed effects describes the evolution of the unperturbed GDP path $\tilde{G}_{t,i}$. (We here consider 5 years running means of annual GDPc and temperature anomalies). Employing equation (3), one time for the observed GDPc and the other time to the counterfactual GDPc reads

$$\begin{cases} \ln G_{t,i}^{\mathrm{obs}} = \alpha_T T_{t,i}^{\mathrm{obs}} + \ln \tilde{G}_{t,i}, \\ \ln G_{t,i}^{\mathrm{cf}} = \alpha_T T_{t,i}^{\mathrm{cf}} + \ln \tilde{G}_{t,i}, \end{cases} \tag{4}$$

where the superscripts *cf* and *obs* denote counterfactual and observed quantities, respectively. Solving equation (4) for $\ln G_{t,i}^{\mathrm{cf}}$ then yields

$$\ln G_{t,i}^{\mathrm{cf}} = \ln G_{t,i}^{\mathrm{obs}} - \alpha_T T_{t,i}^{\mathrm{obs}} + \alpha_T T_{t,i}^{\mathrm{cf}}. \tag{5}$$

Finally, solving for G^{cf} yields,

$$G_{t,i}^{\mathrm{cf}} = G_{t,i}^{\mathrm{obs}} \cdot e^{-\alpha_T \Delta T_{t,i}}, \tag{6}$$

where we have introduced $\Delta T_t = T_{t,i}^{\mathrm{obs}} - T_{t,i}^{\mathrm{cf}}$.

The second approach for estimating the impact of climate change on economic productivity follows the results from the panel regression model in [7]; we refer to it as the '*short-term*' case because this method essentially captures the economic response to short-term (e.g. annual to decadal) changes in temperatures. From equation (S3) in [7], supplementary material, the GDPc growth rate,

$$g_{t,i} = \delta(T_{t,i}) + \tilde{g}_{t,i}, \tag{7}$$

can be written as the sum of a loss term $\delta(T_{t,i})$, which depends on temperature $T_{t,i}$, and the unperturbed GDP growth rate $\tilde{g}_{t,i}$. The loss term reads

$$\begin{aligned} \delta(T_{t,i}) = {}& \alpha_1 \Delta T_{t,i} + \alpha_2 \Delta T_{t-1,i} \\ & + (\beta_1 \Delta T_{t,i} + \beta_2 \Delta T_{t-1,i}) \cdot \\ & \times \left(T_{0,i} + \sum_{s=1}^{t-1} \Delta T_{s,i} \right), \end{aligned} \tag{8}$$

where α_1, α_2, β_1, and β_2 are constant factors. The annual changes in temperature are defined as $\Delta T_{t,i} = T_{t,i} - T_{t-1,i}$, where the $T_{t,i}$ represents the annual temperature in country i at time t. The temperature of reference $T_{0,i}$ is in our study defined as the temperature in the year 1901, with $\Delta T_{0,i}$ assumed to be zero.

Like for the first impact method, we can write equation (7) for the observed and counterfactual case:

$$\begin{cases} g_{t,i}^{\mathrm{obs}} = \delta(T_{t,i}^{\mathrm{obs}}) + \tilde{g}_{t,i} \\ g_{t,i}^{\mathrm{cf}} = \delta(T_{t,i}^{\mathrm{cf}}) + \tilde{g}_{t,i} \end{cases} \tag{9}$$

Solving the system of equation (9) for g_i^{cf} and rearranging it by using the relation between growth rate and GDPc, $g_{t,i} = \ln G_{t,i} - \ln G_{t-1,i}$, we can write,

$$G_t^{\mathrm{cf}} = G_{t-1}^{\mathrm{cf}} \cdot e^{g_t^{\mathrm{obs}} - \Delta \delta_t}, \tag{10}$$

where we have suppressed the subscripts for the country and introduced $\Delta \delta_t = \delta(T_t^{\mathrm{obs}}) - \delta(T_t^{\mathrm{cf}})$. By iterating equation (10), we can express the GDPc at time t by its initial value at time t_0,

$$\begin{aligned} G_t^{\mathrm{cf}} = {}& G_{t_0}^{\mathrm{cf}} \cdot e^{\sum_{t'=t_0+1}^{t} g_{t'}^{\mathrm{obs}}} \\ & \cdot e^{\sum_{t'=t_0+1}^{t} -\Delta \delta_{t'}}. \end{aligned} \tag{11}$$

Since by definition, $G_{t_0}^{\mathrm{cf}} = G_{t_0}^{\mathrm{obs}}$, the final relation between the observed and counterfactual GDPc at a given time t reads

$$G_t^{\mathrm{cf}} = G_t^{\mathrm{obs}} \cdot e^{\sum_{t'=t_0+1}^{t} -\Delta \delta_{t'}}. \tag{12}$$

When constructing the counterfactual GDPc from counterfactual temperature data, we assume that a change in temperature does not affect any other variables that in turn affect economic growth, beyond what is already captured in the estimated impact coefficients. It is hard to verify whether these really capture all, direct and indirect effects of temperature on growth, but we assume that any additional interactions are small enough so that our counterfactual provides a good first–order approximation of the effect of past climate change on GDPc.

2.4. Parameter estimation

The estimation process follows three steps, schematically introduced here and described more in detail in the supplementary material, section 1.2.

(a) Estimation of γ, $\tilde{G}$ and $\widehat{G}$ in equation (2) using observed relative emigration flows, after excluding return and refugee flows. The estimation employs a nonlinear least squares (NLSs) method.

(b) Estimation of the remaining global parameters of equations (1*a*) and (1*b*): a, b, α_p and α_g. a and b are global scaling factors: $a_j = a \cdot \tilde{a}_j$, $b_i = b \cdot \tilde{b}_i$. The parameters of equation (2) are set to the values estimated at step (i). We use the original

Table 1. Migration model and climate change effect parameters. The origin GDPc parameters are estimated from relative emigration flows with 66% confidence level. The remaining parameters are estimated from the bilateral migration data and reported with a confidence level of 99%. The values of the parameters for the climate change effect are taken from [7] and therefore expressed without a confidence level.

Variable	Parameter	Value used
Emigration and transit migration		
Intercept	a	0.233 ± 0.004
Diaspora	α_p	0.943 ± 0.003
Dest. GDPc	α_g	0.19 ± 0.01
Orig. GDPc	γ	-0.0016 ± 0.0004
	$\widehat{G}$	$\$35301 \pm 9356$
	$\widetilde{G}$	$\$929 \pm 139$
Return migration		
Intercept	b	0.124 ± 0.001
	R^2	0.69
Climate change effect on GDPc		
Cross-sectional	α_T	-0.023
Panel	α_1	0.00641
	α_2	0.00345
	β_1	-0.00109
	β_2	-0.000718

observed bilateral migration flows and employ a NLS method.

(c) Estimation of the country specific scaling factors: $\tilde{a}_j$ and $\tilde{b}_i$. We use a linear regression method on averaged bilateral flows of the period of interest (1990–2020). The values estimated during step (a) and (b) are used.

The estimates of the global parameters are reported in table 1. The country specific factors are reported in the supplementary material, table S1 and figure S2.

3. Results

We first compare our baseline model estimates with reference data, which consists of a global bilateral flow matrix derived from reported migrant stock data using a pseudo-Bayesian method [38]. In our baseline model we estimate globally about 70 million migration movements in every 5 year period, on average, which is slightly less than in the reference data (which we refer to as observations hereafter, for simplicity) (figure 1(a)). At the country level, the model produces a pattern of mean migration flows broadly similar to the actual one (figures 2(a)–(d)), although the estimated emigration and immigration numbers can differ by more than 100% from their observed values for some very small countries (e.g Kiribati). Nonetheless, for the majority of the larger countries the difference for total emigration lies within a range of $\pm 20\%$

with peaks of $\pm 60\%$ (figure 2(e)). These extremes would have been more frequent if we had not considered country-specific scaling factors (supplementary material figure 3(a)). The regions that show the largest differences are Southeast Asia, Africa, and some countries in East Europe, and Middle East. A possible explanation of the underestimation of emigration, especially in Africa, can be the presence of refugee flows, which are included in the observed data but not sufficiently captured in our model. Immigration flows are somewhat better reproduced for many large countries, and show mainly an underestimation pattern in many regions, apart from some countries in Southeast Asia, Africa, Central and South America (figure 2(f) and supplementary material figure 3(b)). In relation to previous studies, the estimates produced by our model of international migration are comparable in terms of both migrant stocks (figure 2 in [46] and figure 2 in [14]) and return migration flows (table 1 in [40] and figure 7 in [14]).

Keeping these limitations in mind, we now turn to the counterfactual GDPc scenarios. The impacts of historical climate change on GDPc are relatively homogeneously distributed in the long-term impact case, with nearly all countries suffering a loss in GDPc due to climate change (figure 3(a)). In the short-term case, some countries at high northern latitudes see an increase in GDPc due to climate change, and the losses in some of the lower-latitude countries are less pronounced (figure 3(b)). These results are in line with previous findings for past [6] and future climate effects on GDPc [7].

These economic losses translate into changes in migration patterns in our model. We find that, through its effect on macroeconomic development, climate change may have led to an increase in many bilateral migration flows, amounting to roughly 0.4%–0.5% more migrant movements globally per 5 year period; and simultaneously, to a decrease in other migration flows, amounting to roughly 0.5%–0.7% less migrant movements (figure 1(b)). These numbers are similar between the long-term and the short-term economic response case, except for larger decreasing flows in the former. Therefore, the net difference in global migration numbers is rather different between the two cases: about 0.15% in the long-term case, but only about 0.05% in the short-term case.

These numbers highlight that net change as a single global figure may not be a very meaningful metric when it comes to describing the effect of climate change on migration, since the sign of the effect may differ among country pairs. Somewhat more meaningfully, the gross difference—adding up the absolute values of both increases and decreases—is about 0.9% in the long-term case, and about 1.1% in the short-term case. This number may be interpreted as the percentage of total number of moves that were potentially affected—either induced or inhibited—by
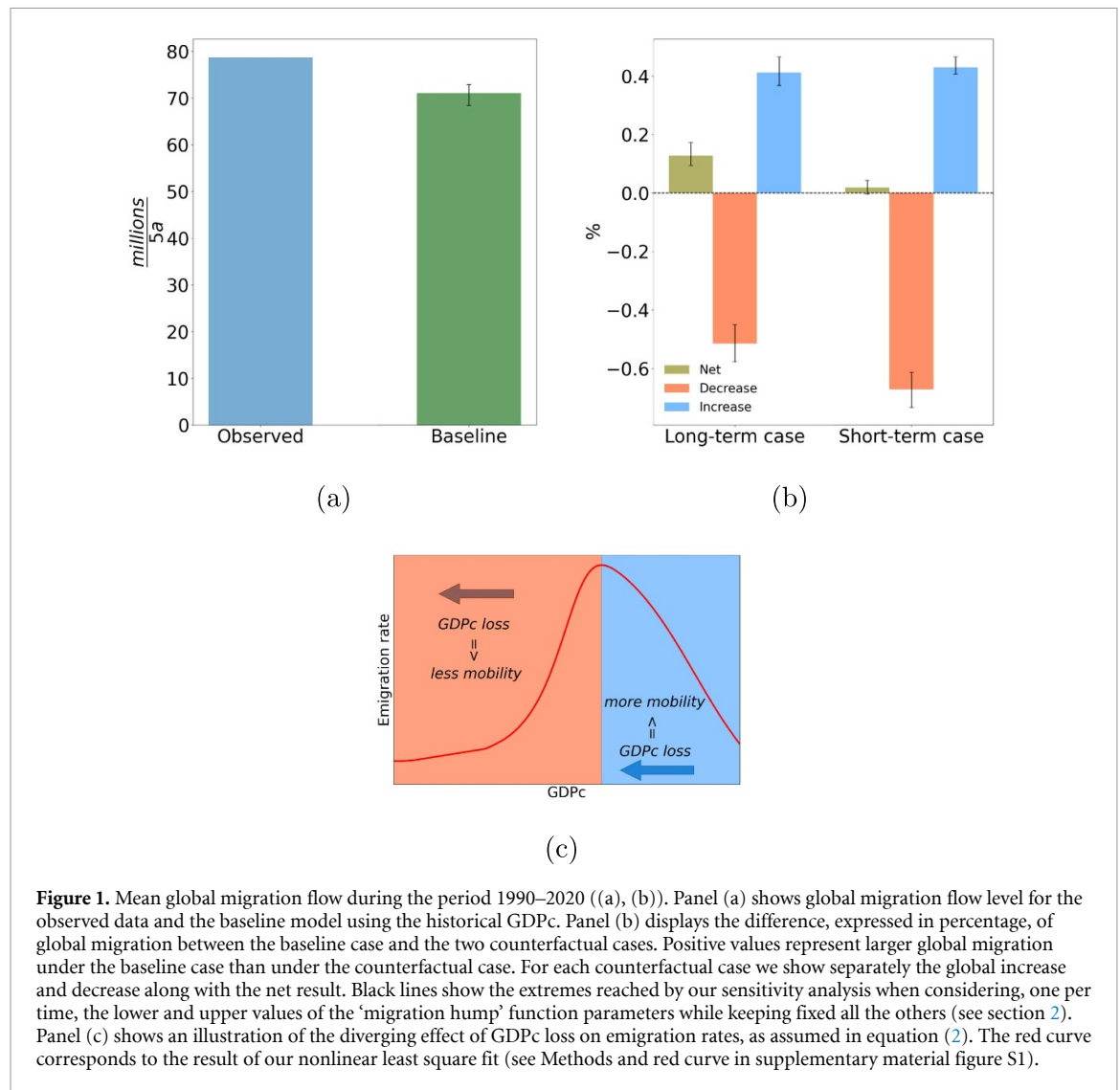
Figure 1. Mean global migration flow during the period 1990–2020 ((a), (b)). Panel (a) shows global migration flow level for the observed data and the baseline model using the historical GDPc. Panel (b) displays the difference, expressed in percentage, of global migration between the baseline case and the two counterfactual cases. Positive values represent larger global migration under the baseline case than under the counterfactual case. For each counterfactual case we show separately the global increase and decrease along with the net result. Black lines show the extremes reached by our sensitivity analysis when considering, one per time, the lower and upper values of the 'migration hump' function parameters while keeping fixed all the others (see section 2). Panel (c) shows an illustration of the diverging effect of GDPc loss on emigration rates, as assumed in equation (2). The red curve corresponds to the result of our nonlinear least square fit (see Methods and red curve in supplementary material figure S1).
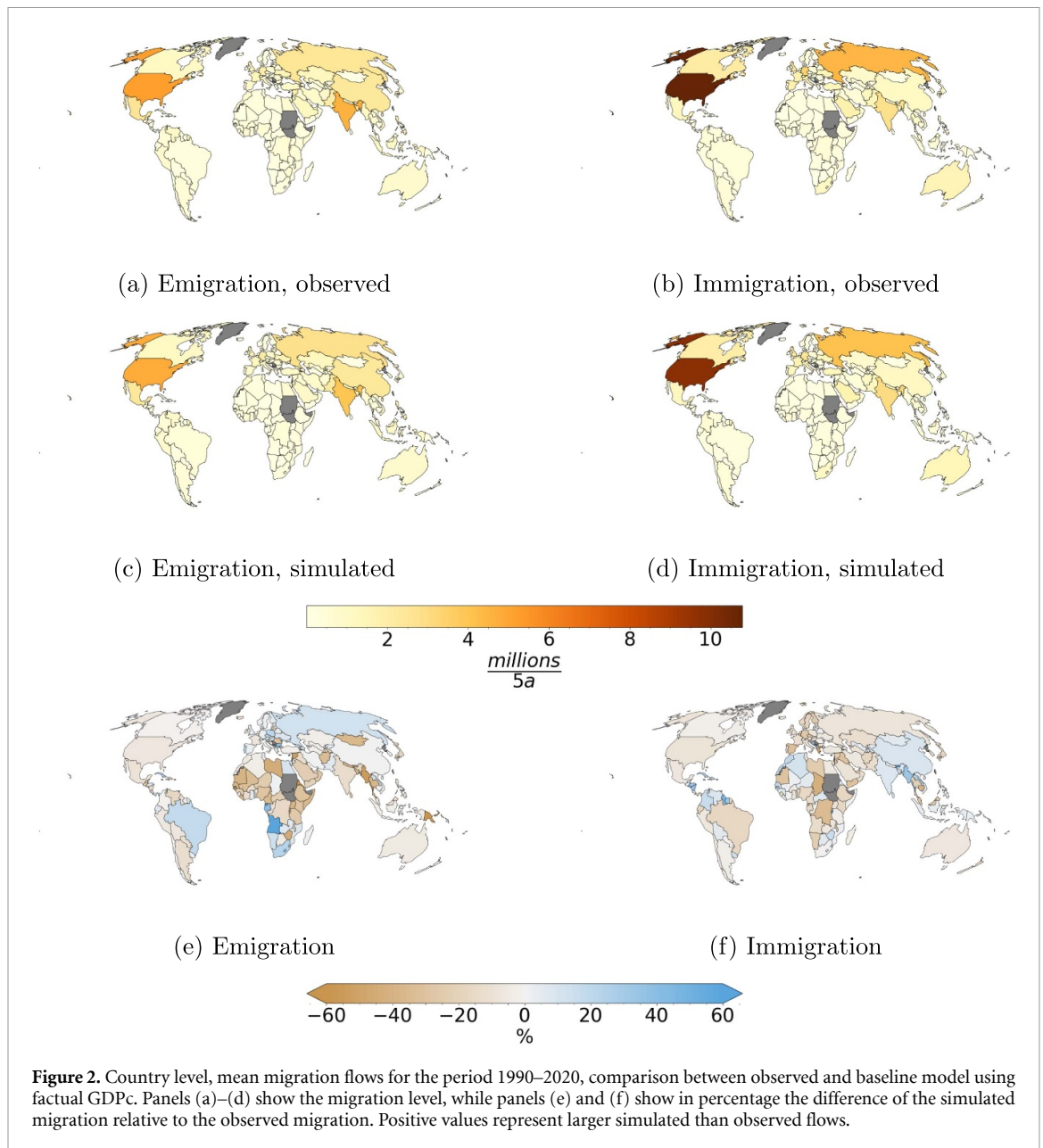
climate change and suggests that the accumulated effects of historical climate change on national economies may be seen as a small but significant long-term contributor to current global migration flows.

At the country level, the geographical patterns of climate-induced migration change are again relatively similar between the short-term and long-term case. It is mostly countries in Sub-Saharan Africa and South Asia that see a decrease in both emigration and immigration due to climate change (figure 4). Most other countries see either little change or an increase in migration, both in and out, due to climate change. This pattern can be understood on the basis of equation (2), where a decrease in GDPc gives rise to a decrease or increase of the emigration rate of the country depending on whether its GDPc lies respectively on the left or right side of the peak of the 'migration hump' function (figure 1(c) and supplementary material figure S1).

Notwithstanding this broad global pattern, results for individual countries can differ strongly between the short-term and the long-term case; countries at high northern latitudes, for instance,

have seen emigration increased by climate change according to the long-term impact calculation, but reduced according to the short-term impact calculation. Indeed, for the northern countries who have crossed the peak of the 'migration hump' function, a loss in GDPc, under the long-term case, corresponds to larger emigration rates while a gain in GDPc, happening under the short-term case, would translate into lower emigration rates (figure 1(c)). These and some other countries—e.g. in Western and Central Asia—also show divergent effects between emigration and immigration.

Complementing the country-level immigration and emigration results, we also analyze changes in directed bilateral flows at the regional level (figure 5). Again, results are qualitatively similar between the two cases, although the magnitudes of change differ. We find that climate change has reduced migration within Africa, South Asia and West Asia; while it has increased migration within Europe and the former Soviet Union. With respect to flows between regions, climate change is estimated to have increased migration to North America from Europe, East Asia

Figure 2. Country level, mean migration flows for the period 1990–2020, comparison between observed and baseline model using factual GDPc. Panels (a)–(d) show the migration level, while panels (e) and (f) show in percentage the difference of the simulated migration relative to the observed migration. Positive values represent larger simulated than observed flows.
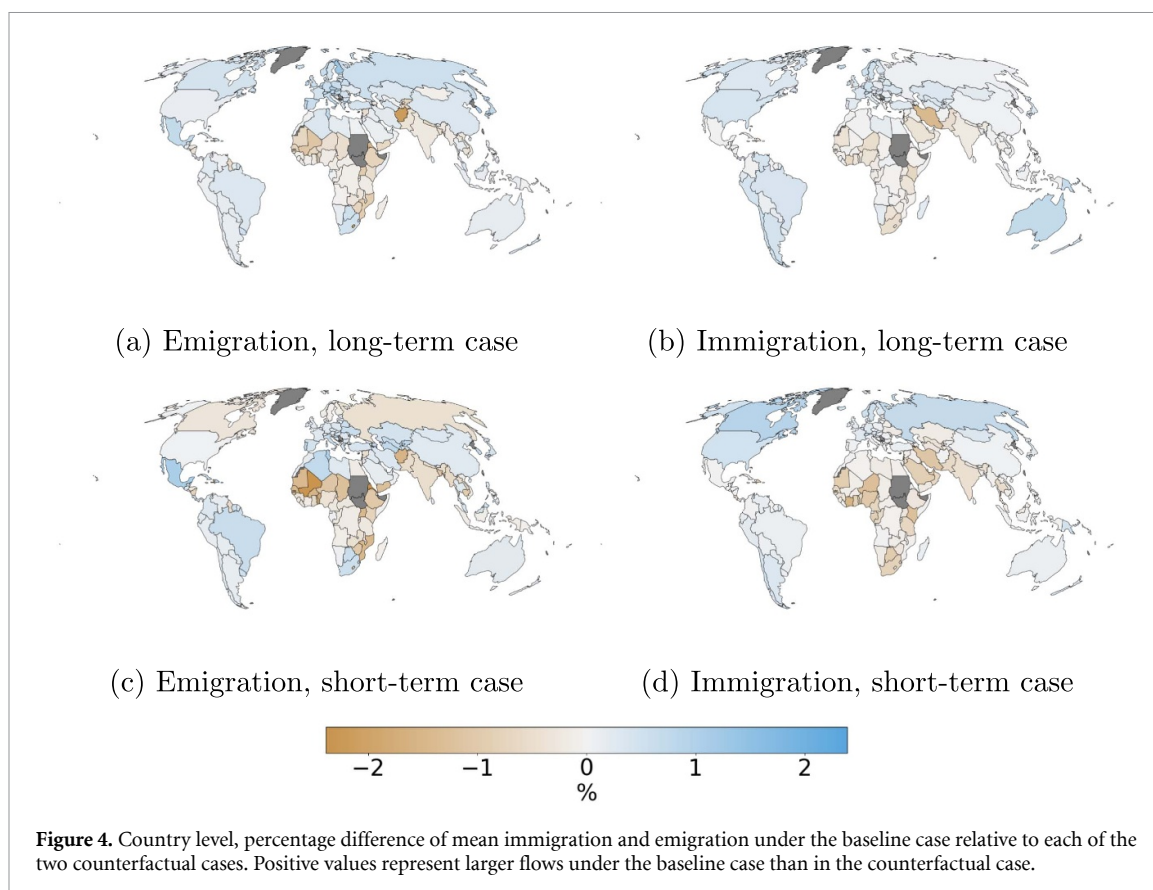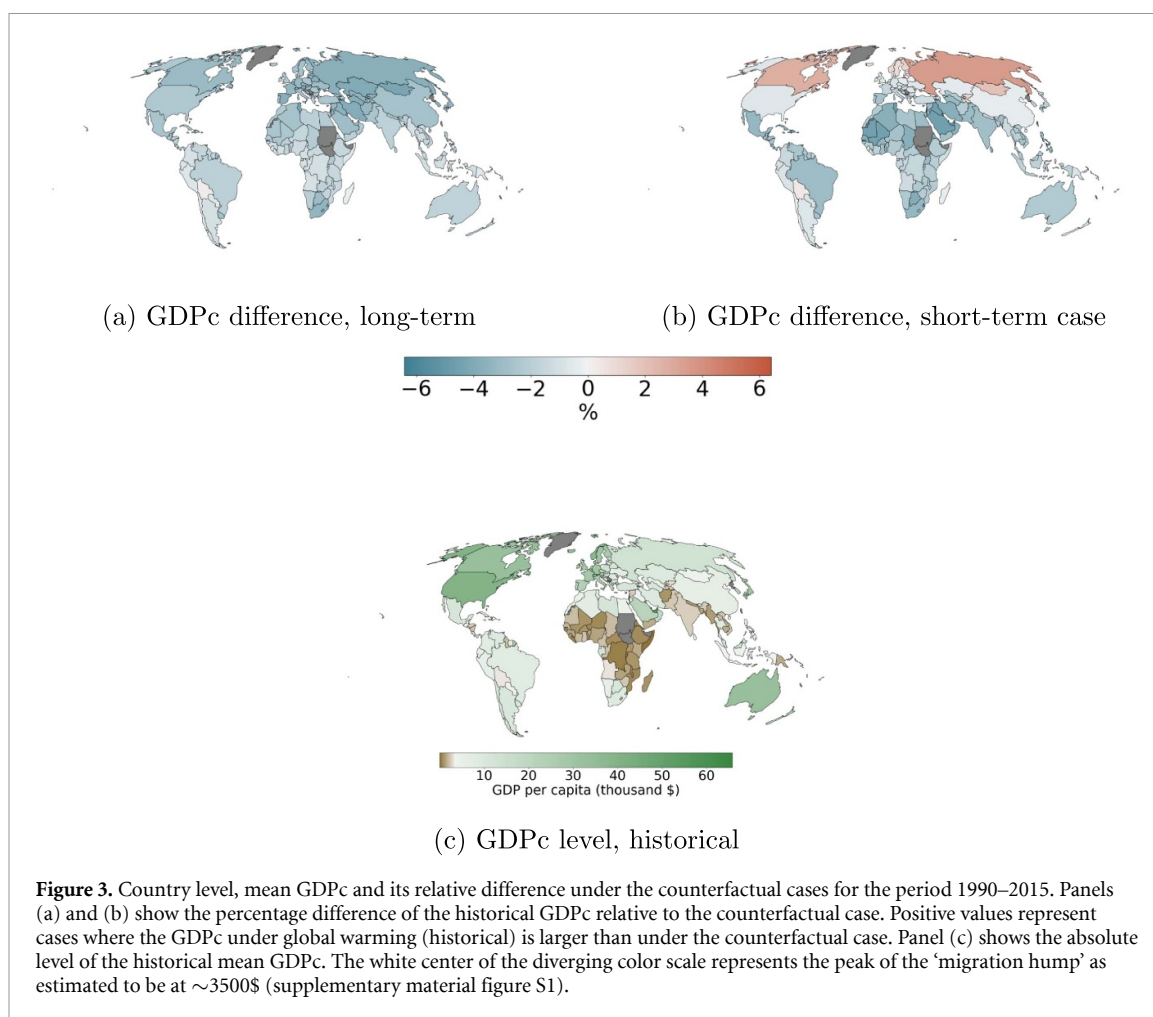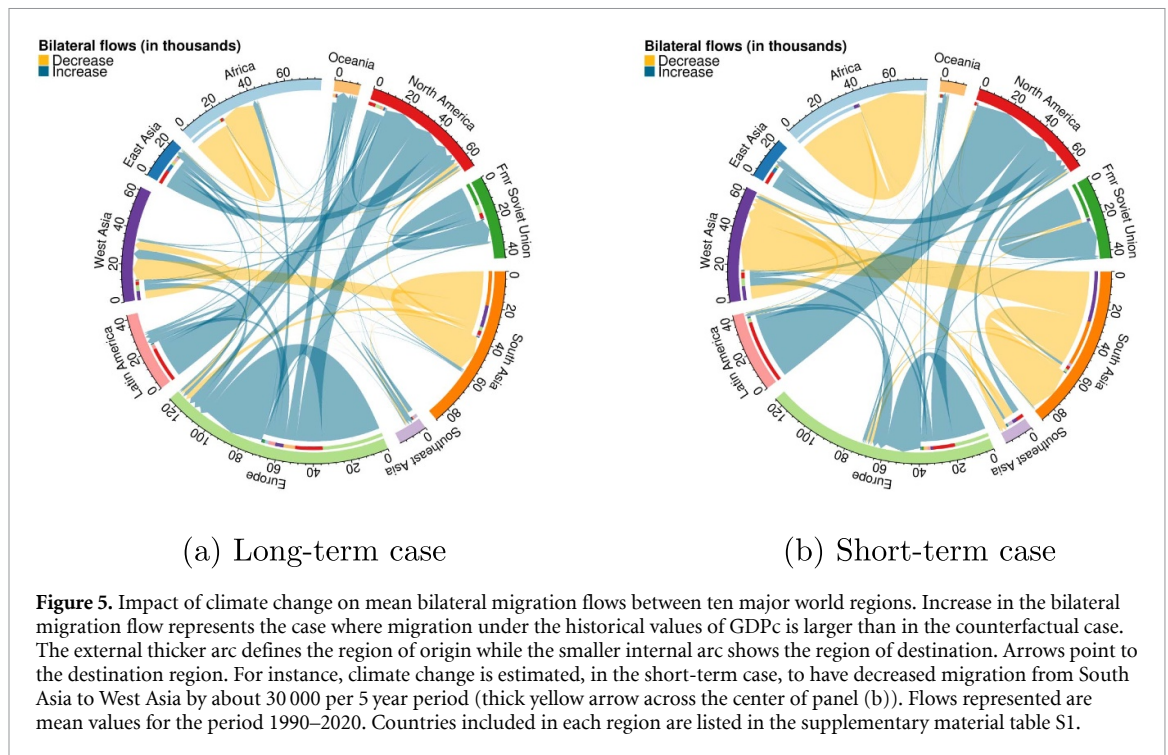
and Latin America. The latter is largely due to migration from Mexico to the USA. Smaller increases are also found in both directions, for instance, between Europe and West Asia, or Europe and Oceania. Remember that our migration model includes return migration, which for some of these flows can be an important factor [40]. Further, we find a decrease in migration from South Asia to West Asia. Remarkably, there is hardly any change in migration between Africa and Europe, or between either of South and Southeast Asia, and any of North America, Europe, and Oceania. Thus, according to our model calculations, climate change has hardly affected migration between the richer and the poorer part of the world, or between what may be called the Global North and the Global South. This may appear counter-intuitive, given that South–North migration is often at the focus both of public debate in countries of the Global

North, and of policy considerations regarding the potential impact of climate change on migration [47].

However, these patterns of climate change impacts on migration can be understood from the functional relationships between migration and its drivers assumed in our models. Emigration rates depend on countries' position relative to the 'migration hump', whose peak is at about a GDPc of ∼3500\$ (supplementary material figure S1). Consider a country where climate change had a negative impact on GDPc, i.e. GDPc is higher in the counterfactual than in the baseline scenario; which is true for most countries in the long-term case (figure 3(a)). A relatively rich country (GDPc above the peak value, i.e. the country is located on the declining branch of the emigration-GDPc relationship (figure 1(c)); green in figure 3(c)) would have seen less emigration in the counterfactual no-climate change world. Conversely,

Figure 3. Country level, mean GDPc and its relative difference under the counterfactual cases for the period 1990–2015. Panels (a) and (b) show the percentage difference of the historical GDPc relative to the counterfactual case. Positive values represent cases where the GDPc under global warming (historical) is larger than under the counterfactual case. Panel (c) shows the absolute level of the historical mean GDPc. The white center of the diverging color scale represents the peak of the 'migration hump' as estimated to be at ∼3500$ (supplementary material figure S1).

Figure 4. Country level, percentage difference of mean immigration and emigration under the baseline case relative to each of the two counterfactual cases. Positive values represent larger flows under the baseline case than in the counterfactual case.

(a) Long-term case   (b) Short-term case

Figure 5. Impact of climate change on mean bilateral migration flows between ten major world regions. Increase in the bilateral migration flow represents the case where migration under the historical values of GDPc is larger than in the counterfactual case. The external thicker arc defines the region of origin while the smaller internal arc shows the region of destination. Arrows point to the destination region. For instance, climate change is estimated, in the short-term case, to have decreased migration from South Asia to West Asia by about 30 000 per 5 year period (thick yellow arrow across the center of panel (b)). Flows represented are mean values for the period 1990–2020. Countries included in each region are listed in the supplementary material table S1.

a relatively poor country (GDPc below the peak value, i.e. the country is located on the increasing branch of the emigration-GDPc relationship (figure 1(c)); brown in figure 3(c)) would have experienced more emigration in the counterfactual than in the factual world. The reverse is true for countries where the impact of climate change on GDPc was positive in the past period, as for some northern countries in the short-term impact case (figure 3(b)).

On the side of the destination country, the relationship between immigration and GDPc is monotonic: the richer a country is relative to other potential destination countries, the more attractive it is for immigrants. These two relationships—the effects of origin and destination GDPc—combine to yield the total effect of a counterfactual GDPc distribution on bilateral migration flows.

The resulting changes in country-level gross flows, or in region-level bilateral flows, can be quite complex because these flows are aggregated from many different individual flows; and because flows to one destination depend on the GDPc in all other destinations. Nonetheless, the above considerations explain the broad pattern of climate impacts that we observe: climate change, by negatively impacting GDPc, has put poorer countries further away from the peak of the emigration-GDPc relationship, and thus has acted to decrease emigration from those countries (figures 4(a) and (c)). Since much of that emigration is to countries within the same world region, we see decreasing flows within Africa, South Asia, and West Asia (figure 5). At the same time, climate change has also negatively impacted many of the richer countries, but this has put them

closer to the peak of the 'migration hump', and thus acted to increase outmigration. Therefore, we find an increase in the migration flows originating from those countries, which are mostly within and between the richer regions of the world. In the short-term case, these divergent changes are reinforced by the fact that countries at higher latitudes tend to be impacted less negatively, or even positively, by climate change (figure 3(b)), and thus become relatively more attractive as destination countries for immigrants from other parts of the richer world; while migration within poorer regions is reduced even more because not only outmigration is suppressed, but also the typical destination countries within the region become less attractive.

4. Discussion

Our modeling study has aimed to explore the potential effect of climate change on migration through economic development, as implied by current theories; in particular, the migration (or mobility) transition. The overall pattern emerging is that recent climate change has acted to increase mobility in the richer parts of the world, and decrease mobility in the poorest parts of the world, compared to a counterfactual scenario without climate change. We find little effect on flows between rich and poor countries, and in particular, no sign that climate change has increased migration from Africa or South Asia to Europe, North America, or Australia and New Zealand (which make up most of our Oceania region). That said, there are still vast income differences across the richer part of the world, and

we do find higher migration due to climate change from some middle-income to high-income regions, for instance, from Latin America to North America. It is important to point out that our model does not consider the effect of past climate change on internal migration or displacement.

The precise quantitative results of our model experiment should not be over-interpreted, but the finding that around 1% of migration moves globally may have been affected suggests that climate change impacts, through the macroeconomic channel, are already now a significant factor influencing migration patterns. On the other hand, they are still less influential than other drivers of migration, such as economic inequalities that would be present even without climate change, but also education, as well as demographic, social or cultural factors [48]. This may not be surprising, but our quantitative estimate, as rough as it may be, adds important substance to scientific as well as public debates about the relative role of climate change in migration [47]. Such quantitative estimates are rare in the current literature, and mostly limited to country-level case studies, from which it is difficult to synthesize a global picture [32]. Perhaps even more importantly, our study also shows how a single metric such as global net migration can be misleading when climate change effects are very different between regions or subpopulations, and that impacts in some regions can be much larger than, or even opposite to, those in other regions. Discussions about policies related to migration and climate change may thus also profit from accounting for such heterogeneities, rather than centering around whether or not climate change leads to migration.

Our results are shaped by a few key assumptions that are motivated by the empirical and theoretical literature on international migration (see supplementary material section 2 for an extended discussion). Existing bilateral migrant stocks—diasporas—exert a large influence on migration flows [49], and thus changing conditions in destination countries primarily affect immigration from countries with which strong bilateral links already exist. Absolute income levels in countries of origin determine emigration rates, while relative income differences between potential destination countries influence the distribution of emigration flows across destinations [50]. At the same time, the dependence of emigration rates on incomes of the origin country is non-linear, with intermediate levels of national income corresponding to the highest emigration rates [11].

Importantly, while many of these relations explain spatial patterns well, there is not yet agreement on whether they also explain observed temporal trends. This means that the model cannot predict actual migration flows at a given point in time. Rather, it illustrates the dynamics brought about by the

long-run driving mechanisms assumed to underlie global migration patterns. While this is a limitation, it is at the same time an important advancement to include potential non-linearities, such as that related to the 'migration hump', into quantitative projections or scenarios of global migration, which so far often rely on linear scaling relations [51] or extrapolation of past trends [35, 52], or on autoregressive models that do not explicitly account for the mechanisms driving changes in migration [53].

With respect to the GDPc impact, there has been considerable research into the impacts of weather variability on economic output in recent years [e.g. 2, 3, 54–57]. The methods employed here to calculate the impacts of temperature variability on GDPc [7] are thought to substantiate previous efforts [e.g. 4, 58] in two regards. First, we employ a cross sectional in addition to a panel regression analysis (labeled 'long-' and 'short-term' in this study, respectively). While the panel regression analyses allow to capture the economic response to short-term (e.g. annual to decadal) changes in temperatures, the cross-sectional analyses can better capture potential long-term adaptation of economies to gradual changes in climate. Second, by using sub-national GDPc data, the statistical power of the regressions may be improved compared to previous analyses based on national GDPc data.

In any case, all these recent studies consistently report that temperature variability affects the level of economic activity in a country. Still, it remains unresolved e.g. to what level economies, and societies as a whole, may either adapt successfully to gradual climate change, including changes in the occurrence of extreme weather events, thus lowering damages to the economy; or on the contrary, be impacted even more strongly, by climatic conditions increasingly transgressing the bounds of historical variability, than can be derived from recent observations. Our estimates using two different methods to calculate the GDPc impacts ('short'- and 'long-term') give an indication of the possible range of outcomes, though probably not a complete one.

Given these and other limitations, our study should be interpreted as a first, crude step towards quantifying a particular aspect of the effect of climate change on international migration. It is, to our knowledge, the first attempt to attribute the effect of past climate change on human migration patterns through a particular impact channel—the accumulated macroeconomic effects of climate change at the country level. Further research is needed to not only refine the approach presented here, but also develop ways to model other impact channels as well as potential interactions between different channels, in order to reach a more complete understanding of how climate change does and will affect patterns of human migration.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Acknowledgments

Author contributions

A R, J S and A L designed the research. A R performed the modeling work and data analysis. C O conducted economic analysis. J S and A R wrote the paper, with contributions from C O.

Conflict of interest

The authors declare no competing interests.

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