Modeling global human migration dynamics under climate change

von
Albano Rikani

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Gutachter: Prof. Anders Levermann
Gutachter: Prof. Jürgen Kropp
Gutachter: Prof. Peter Siedentop

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Zusammenfassung

Die internationale Migration ist in den letzten Jahrzehnten ein zunehmendes Phänomen, das alle Regionen der Welt betrifft. Die wirtschaftlichen Bedingungen sowohl im Herkunfts- als auch im Zielland gelten als wichtige Triebkräfte der internationalen Migration. Die wirtschaftlichen Auswirkungen des Klimawandels haben sich in der Vergangenheit bereits messbar auf die internationalen Migrationsströme ausgewirkt, und künftige Auswirkungen werden dies wahrscheinlich ebenfalls tun.

Diese Dissertation zielt darauf ab, dieses Thema zu untersuchen. Zunächst habe ich ein globales bilaterales internationales Migrationsmodell entwickelt, das explizit die wichtigsten Triebkräfte der internationalen Migration berücksichtigt. Ich habe dieses Migrationsmodell für die Erstellung retrospektiver und zukünftiger Projektionen der internationalen Migrationsströme weltweit verwendet. Die Ergebnisse zeigen, dass das Modell die Muster und Trends der Vergangenheit gut wiedergibt, und die Zukunftsprojektionen verdeutlichen, dass je nach den Annahmen über die künftige Entwicklung des Einkommensniveaus und der Ungleichheit zwischen den Ländern die Migration gegen Null gehen oder in vielen Ländern bis zum Ende des Jahrhunderts noch hoch sein könnte.

Anschließend betrachte ich eine kontrafaktische Vergangenheit, in der der Klimawandel keine Auswirkungen auf die wirtschaftliche Produktivität hat. Ich vergleiche die kontrafaktischen Migrationsströme mit den faktischen Strömen. Die Ergebnisse zeigen, dass es in einer kontrafaktischen Welt ohne Klimawandel weniger globale Migration gegeben hätte. Dieser Effekt wird sogar noch größer, wenn ich den Anstieg und den Rückgang der Migrationsströme getrennt betrachte.

Ich wende dieselbe Methodik auf ein Szenario einer zukünftigen globalen Erwärmung von 3°Cüber den vorindustriellen Bedingungen an. Ich komme zu dem Schluss, dass die Folgen des Klimawandels erhebliche Auswirkungen auf die internationalen Migrationsströme haben könnten, indem sie die relative wirtschaftliche Attraktivität der Zielländer verändern oder das Wirtschaftswachstum in den Herkunftsländern beeinträchtigen, wodurch einige Wanderungen verhindert und andere ausgelöst werden.

Insgesamt deuten meine Ergebnisse darauf hin, dass der Klimawandel möglicherweise erhebliche Auswirkungen auf die globalen Muster der internationalen Migration hatte und auch weiterhin haben wird. Es wird auch deutlich, dass wir, um die Auswirkungen des Klimawandels auf die internationale Migration vollständig zu verstehen, über die Nettoeffekte hinausgehen und die induzierten und gehemmten Ströme getrennt betrachten müssen.

Abstract

International migration has been an increasing phenomenon during the past decades and has involved all the regions of the globe. Together with fertility and mortality rates, net migration rates represent the components that fully define the demographic evolution of the population in a country. Therefore, being able to capture the patterns of international migration flows and to produce projections of how they might change in the future is of relevant importance for demographic studies and for designing policies informed on the potential scenarios. Existing forecasting methods do not account explicitly for the main drivers and processes shaping international migration flows: existing migrant communities at the destination country, termed diasporas, would reduce the costs of migration and facilitate the settling for new migrants, ultimately producing a positive feedback; accounting for the heterogeneity in the type of migration flows, e.g. return and transit flows, becomes critical in some specific bilateral migration channels; in low- to middle- income countries economic development could relax poverty constraint and result in an increase of emigration rates.

Economic conditions at both origin and destination are identified as major drivers of international migration. At the same time, climate change impacts have already appeared on natural and human-made systems such as the economic productivity. These economic impacts might have already produced a measurable effect on international migration flows. Studies that provide a quantification of the number of migration moves that might have been affected by climate change are usually specific to small regions, do not provide a mechanistic understanding of the pathway leading from climate change to migration and restrict their focus to the effective induced flows, disregarding the impact that climate change might have had in inhibiting other flows.

Global climate change is likely to produce impacts on the economic development of the countries during the next decades too. Understanding how these impacts might alter future global migration patterns is relevant for preparing future societies and understanding whether the response in migration flows would reduce or increase population's exposure to climate change impacts.

This doctoral research aims at investigating these questions and fill the research gaps outlined above. First, I have built a global bilateral international migration model which accounts explicitly for the diaspora feedback, distinguishes between transit and return flows, and accounts for the observed non-linear effects that link emigration rates to income levels in the country of origin. I have used this migration model within a population dynamic model where I account also for fertility and mortality rates, producing hindcasts and future projections of international migration flows, covering more than 170 countries. Results show that the model reproduces past patterns and trends well. Future projections highlight the fact that,

depending on the assumptions regarding future evolution of income levels and between-country inequality, migration at the end of the century might approach net zero or be still high in many countries. The model, parsimonious in the explanatory variables that includes, represents a versatile tool for assessing the impacts of different socioeconomic scenarios on international migration.

I consider then a counterfactual past without climate change impacts on the economic productivity. By prescribing these counterfactual economic conditions to the migration model I produce counterfactual migration flows for the past 30 years. I compare the counterfactual migration flows to factual ones, where historical economic conditions are used to produce migration flows. This provides an estimation of the recent international migration flows attributed to climate change impacts. Results show that a counterfactual world without climate change would have seen less migration globally. This effect becomes larger if I consider separately the increase and decrease in migration moves: a figure of net change in the migration flows is not representative of the effective magnitude of the climate change impact on migration. Indeed, in my results climate change produces a divergent effect on richer and poorer countries: by slowing down the economic development, climate change might have reduced international mobility from and to countries of the Global South, and increased it from and to richer countries in the Global North.

I apply the same methodology to a scenario of future 3°C global warming above pre-industrial conditions. I find that climate change impacts, acting by reorganizing the relative economic attractiveness of destination countries or by affecting the economic growth in the origin, might produce a substantial effect in international migration flows, inhibiting some moves and inducing others.

Overall my results suggest that climate change might have had and might have in the future a significant effect on global patterns of international migration. It also emerges clearly that, for a comprehensive understanding of the effects of climate change on international migration, we need to go beyond net effects and consider separately induced and inhibited flows.

To those who had to migrate.

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1 Introduction

According to the recent report from the International Organization for Migration (IOM) the number of international migrants[1] has increased substantially over the past decades, with the estimated number in 2020 (281 millions) being larger than three folds the estimated value in 1970 (84 millions) [1]. While the majority of international migrants resides in regions characterized by high levels of economic development, e.g. Europe and North America, international migration is a global phenomenon involving all the regions of the globe [1]. Through the transfer of skills, money and norms, migration influences economic and demographic aspects at both the country of origin and destination [2, 3, 4, 5]. Therefore, being able to produce projections of the future evolution of migration flows is of great academic and social interest.

In particular, migration is a complex phenomenon adopted in response to economic, demographic, environmental, social and political conditions [6, 7], with the ultimate aim of improving life conditions, in the short or long term. In a context of intertwined factors defining the migration decision, climate change may act, directly or indirectly, reshaping the motivations or conditions for migrating [8, 9]. At the same time, impacts of climate change have already appeared across the globe and have affected almost all natural and human systems. The last report from the Intergovernmental Panel on Climate Change (IPCC) shows that losses in terrestrial and marine ecosystems are approaching an irreversible point, both water and food security have been reduced, altogether provoking adverse socio-economic consequences [10]. These climate-change-driven impacts may have already influenced global migration patterns. Global warming is projected to increase and the impact of future climate change on migration may be substantial [11]. Therefore, investigating the changes in international migration patterns due to climate change impacts appears of relevant importance for understanding how societies have reacted in the past and for preparing them to the response that might take place under future climate change impacts.

[1] There can be different definitions of an international migrant, depending on the scope and area of study. Here, and throughout this work, an international migrant is defined as a person living in a country different from that of birth.

The work presented in this thesis aims at studying these aspects. To this end I have built a global migration model which accounts for the important drivers and processes that shape international migration flows. The model has been used within a dynamic population model where fertility and mortality rates, as well as net migration flows define the temporal evolution of the population. In a second step I have used the international migration model for investigating the impact of climate change on migration patterns during the past three decades. The impact of climate change on the economic productivity has been used as the channel of transmission of the impact from climate change to migration. In the last part, focusing on the same macroeconomic channels of impact of climate change, I investigate the response of international migration to a future level of global warming.

Before describing in detail the methods and results obtained during my research, summarised in these three aspects, I will proceed in section 1.1 with a brief introduction to the international migration theory, discussing the main drivers of international migration, with a focus on the role of climate conditions. In section 1.2 I will go shortly through the methods usually used to measure both international migration and climate change. In the final section, 1.3, I will briefly outlie the scope of the thesis and the content of the three papers on which this work is based. After this introduction I will proceed in the next three chapters with presenting the methods and discussing the results regarding the development of the global international migration model and its application to past and future scenarios of climate change.

1.1 International migration

When did the phenomenon of migration started? If we try to answer to this question we realize that migration started with us, in principle *Homo sapiens*. More than 60,000 years ago, during the late Pleistocene, multiple dispersal events took modern humans out of the African continent reaching the then new territories of Eurasia [12]. This process of migration and settling in new regions continued: the last major land to be settled being New Zealand, approximately 800 years ago [13]. Across thousands of years, technological innovations and social structure changes have characterized the evolution of the migration phenomenon. When, approximately 10,000 years ago humans, began to domesticate plants, first, and animals, later, their communities went through an enormous structural change, shifting from hunter-gatherers lifestyle to sedentism. Settling, can be seen as the first step towards the appropriation of, or claim on, an area: ultimately setting the roots for defining borders and concepts of inter and intra areas movements. Political systems evolved from simple organizations of small groups of individuals to complex and highly structured nations, with millions of individuals within their borders [14]. The notion of international[2] migration, as the process of leaving one country (origin) for settling temporary or permanently in another country (destination), was born.

1.1.1 The fragmented landscape of migration theories.

Understanding the causes and the heterogeneity of the processes through which they act to produce the migration decision is a complicated task. International migration is a complex

[2] It is important to point out here that this is not a matter of mere terminology. Indeed, internal migration, i.e within the country, may differ profoundly from international migration in its processes and drivers [15, 16, 17].

phenomenon, emerging from a decision taken individually or at the household level, and embedded into a specific economic, political, social, environmental and demographic context. Attempts to obtain a comprehensive understanding of this complex process have led in the past decades to different theories of international migration, usually arising from different socio-economic theories and therefore representing mainly economic migration [18]. Neoclassical economic theory assumes that the main force driving international migration is the gap in real wages between origin and destination countries, and the decision to migrate, taken at the individual level, aims at maximizing the utility, after considering costs of migration [19]. Following closely the neoclassical economic theory, the new economics of labour migration theory shifts the focus from the individual to the household: the migration decision is taken at the household level and aims at minimizing the risk of the household rather than maximizing the income of the individual [20]. Importantly, the new theory also emphasizes the role of relative deprivation at the origin country, which can cause international migration movements even in the absence of wage differentials [21]. Dual labor market theory and world systems theory move further away from the micro-level approach and suggest that are inherent macro-level aspects of our societies, like labour markets in modern economies and inter-governmental ties, that shape migration flows [22]. After a migration channel between two areas is initiated and a community of migrants has settled in the destination country, a process of self amplification, or at least sustainment, intervenes at different scales. As hypothesized by the network and institutional theories, the component of migrants at the destination country, referred as diaspora, and the development of organizations providing potential migrants with legal help, would ease the costs and risks of migration, eventually incrementing future migration flows along specific corridors [18, 23]. Each of these theories tries to explain international migration by considering one specific mechanism and focusing on different spatial scales as well as phases of the migration process. Recently, there has been an attempt to bring all these theories together under a common theoretical framework [24]. Nonetheless, critics to a lack of evolution of the migration theory itself have followed [25], leading to a more recent attempt of conceptualization of migration as a phenomenon in terms of capability and aspiration to migrate [26]. To date, there is no universal acceptance of any of these theories as being the "best" theory of international migration and the apparent fragmented landscape of migration theories [27] has led to considering the possibility that, after all, there might not be any "grand theory" of migration but rather a context-dependent approach to this phenomenon [28, 29].

1.1.2 Modelling international migration.

Testing any of these theories against real data requests a quantitative approach through a mathematical migration model. While there are different approaches for modelling international migration [30], a preponderant quantity of empirical research relies on so called gravity models [31, 32]. In its basic formulation, the gravity model for migration is inspired by Newton's universal law of gravitation [33]: the two masses are substituted by the population size at the origin and destination, their shortest geographical distance replaces the squared distance in the original formula and the gravitational force becomes the migration flow (Equation 1.1):

$$M_{i\to j} = a \cdot \frac{P_i P_j}{d_{ij}}, \tag{1.1}$$

where $M_{i\to j}$ represents the flow from country i to country j, d_{ij} the distance between them, a is a scaling factor and P_i and P_j are the population in origin and destination respectively. The reason for its extensive use in the literature can be found mainly in the fact that this simple model can be easily augmented for including different potential explanatory variables and the effect on migration remains transparent and easy to understand. This is of key value for testing how the multitude of countries' characteristics influences international migration flows [34]. Extensions of the basic gravity model have been used to explore, among others, the influence, in magnitude and direction, of economic, demographic, environmental and socio-political factors on international migration [35, 36, 37, 38, 39]. A representation of an augmented gravity model is reported in Equation 1.2.

$$M_{i\to j} = a \cdot \frac{P_i P_j}{d_{i,j}} \cdot G_j^{\alpha_g} P_{i,j}^{\alpha_p} \tag{1.2}$$

where G_j is the gross domestic product per capita in the country j and $P_{i,j}$ represents the community of people from origin country i living already in the destination j. The exponents are usually factors to be estimated.

Economic drivers, at both origin and destination country, are identified as major determinants in shaping migration flows [40]. Gross Domestic Product (GDP), wages and unemployment rates are among the main variables used for capturing economic conditions. Results from empirical research suggest that: (*i*) unemployment rates at the destination affect negatively immigration flows into these countries [36]; (*ii*) wage differentials between origin and destination have been the main driver of the decreasing phase of migration from Europe to South and North America during the mass migration in the nineteenth century [41]; (*iii*) improvement of the GDP per capita at the destination increases immigration rates [42].

These results, based on simplistic push-pull factors and assumptions from the neoclassical economic theory, that individuals migrate in order to maximize their utility or income, do not capture more complex processes that shape migration: increasing unemployment rates at the origin can be associated with decreasing migration flows [43]; decreasing wage differentials might not stem migration flows from increasing [41]; increase in the GDP per capita level at the origin country might not reduce emigration flows [42]. In other words, a simple linear push-pull effect is not able to explain the rise of emigration rates from low- and middle-income countries in correspondence with socio-economic development, which appears, at a first glance, counter-intuitive. Indeed, economic development in a country would be expected to produce a decrease in emigration rates, since the economic gap between the origin and destination would be reduced. The real-world data shows a quiet different picture: a non-linear dependence of emigration rates on variables, such as the GDP per capita, used as proxies for the economic development [44]. This inverse U-shaped relation, usually referred to as migration hump, implies that minimum values of emigration rates are associated with low- and high- income levels in the origin, while the maximum emigration rates would be observed from middle-income countries (Figure 1.1). This pattern is observed extensively for different type of international migration data and different periods of time [44, 45], appearing already in the mass migration from Europe to the “New World” at the end of the nineteenth century [41].

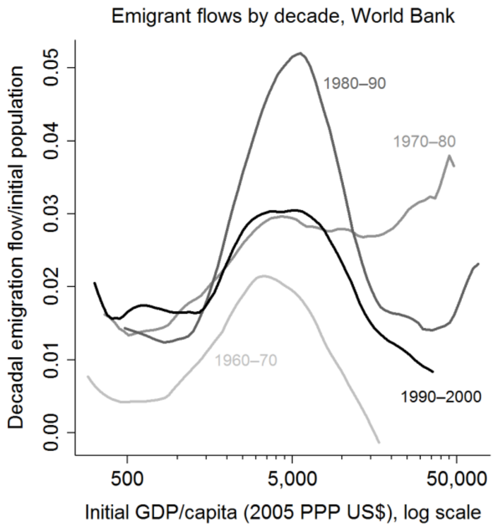


Figure 1.1: Migration hump as estimated in ref. [44]. It shows the results obtained from a non-parametric regression analysis of decadal emigration flows against real income per capita at the starting year of the decade (Adapted from ref. [44]).

During the last decades there has been a major research effort with the aim of understanding the processes driving the emergence of the inverse U-shaped profile of emigration. One strand of discussion has focused on discerning whether this hump shaped pattern is a purely spatial result, rather than the result of a migration transition process which would see the countries tracing the migration hump curve as their economies develop [46]. Different empirical results support this second hypothesis, with countries following a so called emigration life cycle, driven by structural socio-economic and demographic development: with increasing mobility at the first stages of the development process and consequential saturation and convergence to lower levels of emigration rates [45, 41, 47] (Figure 1.2).

In an attempt to fit the multifaceted effect of development on emigration, more recent theories have tried to conceptualize the development-migration nexus, and in general the migration decision process, in terms of aspiration and capability to migrate [48, 49, 26]. A fascinating aspect of this theory is the shift of perspective in studying migration: from an *ex-post* (when the movement already happened) to an *ex-ante* (before the movement takes place) approach. It emphasizes the fact that migration decision is a process that starts much earlier than the concrete movement and, in order to better understand its evolution, we should extend our analysis also to those who remain. Migration decision would start with the desire to migrate, then the individual would go through phases of planning and preparation, until the materialisation of the concrete movement [50]. Along the evolution, from the initial wish to the final materialisation, the capability to migrate would intervene and constrain the final decision [51]. High aspiration alone would probably not be sufficient for a migration event to take place: the gap between the population that expresses the desire to migrate and the actual

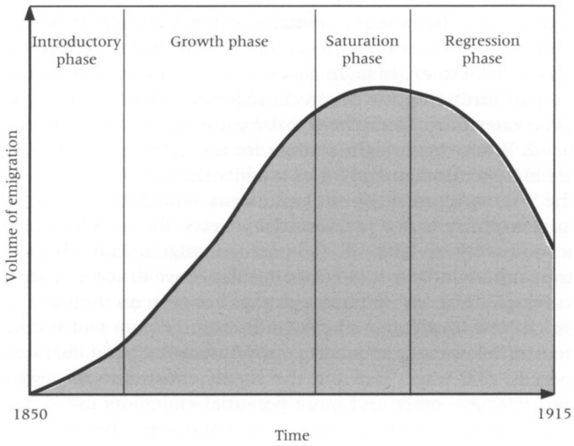


Figure 1.2: Stylized evolution of European mass migration. Emigration life cycle illustrating the temporal evolution of emigration during a period of economic growth. Emigration flows are found to steeply increase in the first stage of economic growth, reaching a saturation point associated with a maximum level of emigration and then falling again to lower levels (Adapted from ref. [41]).

migrants can be large and has been observed already in empirical results covering different regions [50, 52]. On the other hand, a high level of capability alone would not be enough to trigger a migration decision since a high life satisfaction at the origin would reduce aspiration for migrating. Migration decisions would emerge then from the interplay between the desire and capability, and socio-economic development can affect both. For instance, economic and social development can increase migration capabilities by: reducing costs and risks for migrating, e.g. through the introduction of visas [42], and by increasing the budget that people would be able to spend for migrating. Migration aspirations are also affected by a process of socio-economic development taking place in the country of origin. Development can produce, at least in the first stages, an increase in inequality [53] and relative deprivation, i.e. feeling poor in comparison to others in a reference group, resulting in an increase of aspirations. Empirical evidence suggests that both cases could trigger an increase in emigration rates [54, 55]. Development could also improve the access to information and therefore increase the awareness of opportunities abroad, changing the reference group in assessing relative deprivation, hence resulting in increasing aspirations [49, 55]. Demographic transition, together with higher education levels, would result in younger and more educated population, which are associated with higher levels of aspirations [56]. These processes, among others, would explain an increase in emigration rates as countries trace the initial phase of socio-economic development. Later on, the capability, after increasing throughout the development phase, would eventually stabilize at a certain level. Aspirations, on the other hand, would eventually decrease to a minimum as the opportunity gap with the other countries is reduced. Therefore, following the dynamics of aspiration and capabilities, emigration rates, after reaching a maximum, would decrease to a new minimum, ultimately producing the inverse U-shaped profile.

Demographic drivers, left alone the aspiration-capabilities model, have already appeared as important factors in the development-migration nexus. The natural evolution of the population through births and deaths defines both the size and age composition of the population in a country. In particular, high rates of fertility would produce a larger cohort of young population. From a life-cycle perspective, young people have a longer period of time for maximizing the utility and gains from migration. In line with this hypothesis, empirical results suggest that young people are more prone to migrate[3] [42, 52]. Migration flows are driven not only by demographic factors at the origin but also from those at the destination. Indeed, in a scenario of low fertility and mortality rates, countries might need international migrants to keep running their social security and health systems. In this case a pull factor might be put in place by the destination countries that would adjust their immigration policies to attract migrants [57, 58, 59]. At a more micro-level and in line with the new economics of labour migration, the structure and size of the family might influence the migration decision and destination choice with the goal of diversifying the income and minimizing the risk of the household rather than of the individual. Within this perspective, the presence in the household of children or elderly people, as well as being married or not, could have a divergent influence on the decision taken by women and men, unravelling the gendered division aspect of societies and families [60, 61, 62].

Social drivers account for characteristics such as migrant networks abroad. The *diaspora*, i.e. the size of migrants from an origin country that has already migrated to a destination country, is identified as a major driver of migration [35], amplifying itself as theorised already in the cumulative causation theory [18]. The pathways through which the diaspora can foster migration flows, and therefore feed back to its own size, can be different. For instance, it could reduce the risk and increase the benefits of migration. Indeed, migrants already living abroad could help newcomers in finding a house and a job, even before they arrive at the destination. The risks would also be reduced because they would inform and assist newcomers during the preparation of migration and the settling. The diaspora can also act through remittances to let potential migrants overcome poverty constraints. Importantly, the diaspora would also reduce the cultural loss experienced by the new migrants [63]. The positive effect of the network abroad appears substantial across all levels of GDP per capita in the origin country, being the most relevant driver for low-income countries [34]. Besides affecting the size of the migration flows, empirical results suggest that diasporas affect also the skill composition of the new migrants: family reunification and reduced costs of migration produce an increase of the share of unskilled migrants [64, 65].

Political drivers include policies at both origin and destination and cover both the phases of migration and integration at the destination. At the origin country, political instability and lack of political freedom is an important driver of migration [66]. The decision about the destination country is also shaped by immigration policies at the destination and the overall perception of protection [67]. At a macro-level, empirical analysis have been focused on assessing the role and efficacy of migration policies, a major and direct measure that countries implement with the aim of controlling migration, in size and composition (e.g. age and education level) [68]. Unfortunately, empirical results controlling for the effective role of immigration policies in shaping migration suffer from different limitations. First, the temporal and geographical limited coverage of immigration policy datasets, which mainly include countries that are part of the Organisation for Economic Co-operation and Development (OECD). Second, the different indexing measure for the policies, which leaves ambiguous the

[3]Increase in fertility rates per se might produce a reduction in emigration in low and middle income countries [34]. This might be due to the fact that high fertility rates usually describe a first stage of socio-economic development and poverty constraints might still impede aspirations of migration.

comparison between studies that use a different measure of policies[4] [71]. Third, immigration policies are dynamic variables that respond to local and global structural changes [68], and can depend on the migration flows that a country experienced, ultimately blurring any conclusion about a causality effect. Despite these shortcomings, the new datasets of immigration policy index have led to a first stream of empirical studies where the effectiveness of migration policies in shaping migration flows has been investigated. Historical evidence suggests that when immigration policies were used to attract migrants, like the Bracero Program in the US and the Guest worker program in Europe and in the Gulf States [72, 73], migration flows responded positively and the result is backed by empirical studies analysing more recent labour migration policies [74]. On the other hand, it is not clear whether this prompt response is obtained also when countries tighten their policies, in other words, if more restrictive policies are efficient in reducing the flows as more open policies are in attracting migrants. Several empirical studies find a positive response of migration flows to the tightening of immigration policies [37, 36], while others provide evidence for a more complex effect where more restrictive visa policies decrease not only immigration but emigration too, undermining the overall effect of the restriction [75].

Transnational drivers consider cultural, geographical and political factors that connect two or more countries. For instance, a common language is a cultural driver associated with increase in migration between the countries that share it. Geographical distance, on the other hand is commonly associated with a negative effect on migration flows, probably due to the larger costs for migrating at longer distances. Colonial ties, in many cases likely correlating with the common language, the diaspora size and bilateral immigration policy, show a positive effect on migration flows [35, 76]. Even without considering past colonial ties, preferential bilateral migration patterns can arise due to large diasporas emerging and disappearing as nation-states borders evolve. An example can be the population of the countries in the region of the former Soviet Union and Jugoslavia [77]. Last, international migration flows can largely be affected also by the establishment of unions of nations, such as European Union (EU), which introduces the free movement of people within its borders [37].

In this first part of the introduction I have attempted a comprehensive but not complete overview on the international migration theory, as well as on the drivers that shape migration. As already emerged, the drivers shaping this complex phenomenon are many and interlinked. They cover the full spatial scale, from structural characteristics of the household to the international political ties, and temporal scale, from the relatively fast change of economic factors like the GDP per capita to the relatively slow dynamics of geographical borders and transnational organizations. There are though two important drivers, missing in this short resume. The first one is what would fit within the political drivers: conflicts and wars. I intentionally did not include this driver in the list above because it deserves an extensive discussion, probably it would be worth the work of another doctoral thesis. It also appears as a fundamentally different process of migration: (*i*) it is driven substantially by the threat to life, (*ii*) the flows are not comparable, neither in size nor in the time scale on which they develop, to common migration flows, (*iii*) the common policies do not apply to the refugees.

[4] There can be different levels of considering and aggregating the set of policies that a country applies to immigration and therefore an universal quantity measuring immigration policy would be ambiguous [69, 70].

The second important driver that is missing in my discussion is the environmental one. This was also intended: environmental drivers, in terms of climate change impacts, are at the core of this doctoral thesis and I will introduce them in the following section.

1.1.3 Climate change and international migration

Under a broad perspective, climate conditions define the suitability of a certain place for human thriving. This climate niche has been found to correspond to ∼13°C mean annual temperature [78]. Within the niche modelling framework, changing climate conditions have been found as major drivers of human population dynamics during the Last Glacial Maximum (27-19 ky ago) [79]. Other approaches, based on linking climate variables, such as temperature and precipitation, to the net primary productivity, have been used to investigate the effect of climate change on human population dynamics during the late Pleistocene [80]. Importantly, in this case climate conditions are used also for tracking the global expansion of anatomically modern humans, finding that the change in climate conditions are necessary to explain the arrival time of humans in new territories. These studies highlight the fact that climate factors have been major drivers of both human's demographic dynamics and dispersal into different regions, already thousands of years ago.

Since then, the human population has increased substantially, along with societal and technological development. Humans' role in defining global climate conditions has moved from being totally passive, in the sense of having no power of influencing climate variables at the global scale, to being crucial players through activities and technologies that would feed back to the climate system affecting its global stability. The last report from the IPCC shows that human influence has provoked an unprecedented rate of global warming, compared to at least the last 2000 years (Figure 1.3) (IPCC, [81]).

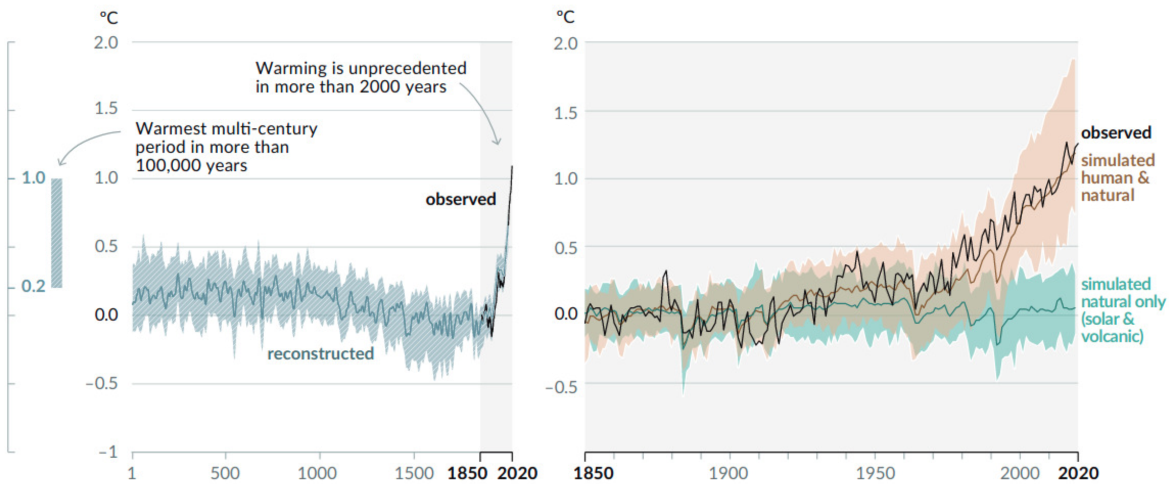


Figure 1.3: History of global temperature change (relative to the 1850-1900 period) and the role of human and natural factors in this change. Left-hand panel shows the change in global surface temperature during the last 2000 years. Grey line and shading represent reconstructed data from paleoclimate archives. The black line represents observations and refers to a more recent period (1850-2020). The right-hand panel shows, for this recent period, the change in global surface temperature as observed and reproduced by climate models where only natural or natural and human drivers were included. Adapted from the Summary for policymakers in[81]

Impacts of such unprecedented global warming have already appeared on terrestrial, freshwater and ocean ecosystems, covering most of the regions of the globe (IPCC, [82, 83]). Thousands of years of human development have resulted also in more complex societal organization which includes complex food production, economic and infrastructure systems, among others. The impact of climate change has been observed in these human-made systems too (IPCC, [84, 85]).

In response to climate change impacts, people might decide to migrate. The climate-related processes that impact natural and human-based systems and influence the migration decision can be grouped on the temporal scale that defines their dynamics. The literature distinguishes between two types: rapid and slow onset events. The former includes events as storms, floods and wildfires, that emerge quickly, on short time scales of days or hours. Their impact can be destructive for human settlements and force people to migrate. Empirical studies find divergent results on whether these rapid events lead to migration events [86, 87]. Review studies suggest that these events might mainly lead to short-distance and temporary migration [88, 89]. On the other hand, processes like droughts and sea-level rise are defined as slow onset processes that develop on a longer timescale compared to the previous ones. The impact of slow onset processes on migration has been investigated mainly through temperature and precipitation variability. Empirical results suggest that temperature variability is associated with emigration to short and long distances while the effect of precipitation variability is less robust [38, 87].

Overall, results show a strong heterogeneity in the migration response to climate change impacts. For instance, the response of migration to climate variability can be country-specific [90], or even community-specific in the same country [91]. Economic conditions in the origin country, in relation to climate impacts, can be a crucial factor conditioning migration in terms of reduced financial capability to finance migration, leading to a poverty trapped population effect [92, 93]. This suggests that, besides specific cases where there is a clear causal effect between the climate event and the migration decision, like settlements being destroyed by floods or hurricanes, the link between climate impact and migration decision might be indirect, acting through secondary variables, and following very complex pathways [39, 8]. Converging on what has already been highlighted in the previous section, many empirical and review studies indicate a multi-factors dynamics characterizing the migration decision: environmental factors need to be included within the broader demographic, political and economic context in order to explain migration decisions (Figure 1.4) [7, 94, 88, 95].

1.2 Measuring international migration and climate change

In order to study the role of the potential drivers of migration, consistent data on international migration is necessary. This is specifically true for migration flow data, that defines the number and characteristics of people that, in a certain period, move from one country to another. Unfortunately, international migration flow data are scarce and affected by different limitations [96]. They are mainly collected by institutes at both origin and destination country, where the measure of migration flows is designed to meet country-specific criteria, resulting in major difficulties in producing cross-section analysis. This appears clear in cases like the international migration flow data collected by the UN, where, in some cases, the flow associated

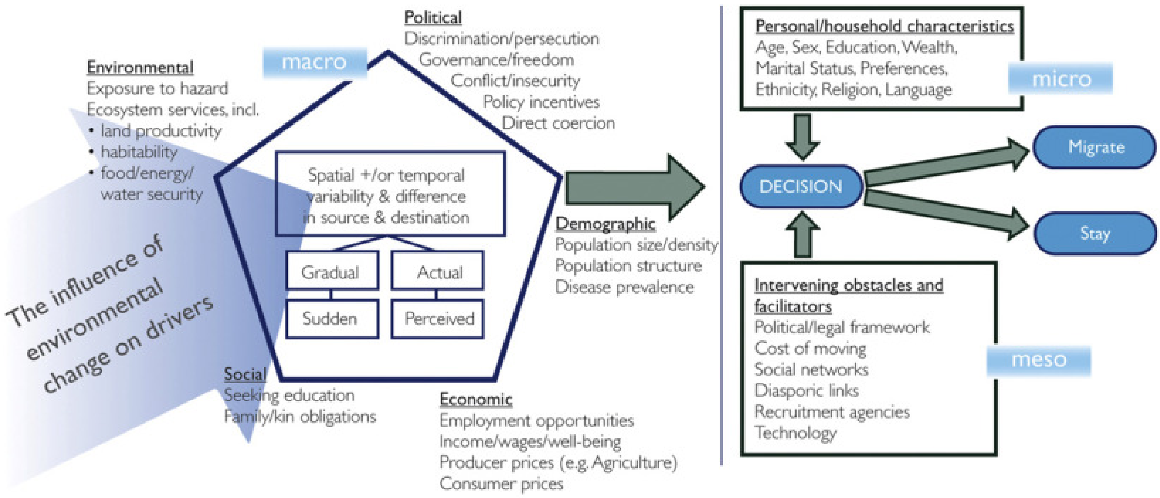


Figure 1.4: Theoretical structure of the drivers intervening in shaping the migration decision (Adapted from ref. [9]).

to a certain population is different when reported by the origin and the destination country [97]. In order to overcome these limitations, a Bayesian model for harmonizing the data has been proposed [98]. The shortfall of this and similar methods is the limited number of countries for which migration flow data are in principle available. Moreover, this limitation could lead to biased results since these database mainly include developed countries as destination. This would constrain the analysis, excluding migration flows between developing countries. This is a major limitation since South-South migration accounts for the largest share in the global level of migrant population [99], and climate change impacts, representing an important challenge in these regions, could have significant effects on South-South flows.

In order to circumvent these difficulties, recent studies have focused on bilateral migrant stocks rather than flows. Making an extensive use of national censuses and population registers they have built global matrices of bilateral migrant stocks spanning different decades [100, 99]. Then, other studies have used these matrices to construct estimates of migration flows by simply taking the difference of two consecutive matrices of migrant stocks [39, 35]. Different issues are associated to this method of estimating migration flows. For instance, assumptions have to be made when the difference in the stocks is negative. In this case the result can be due to return migration, or movements to a third country. Moreover, the change in a specific migrant stock is the result of natural processes as well, such as deaths and births[5]. Accounting for these different channels of migration and natural demographic adjustments has represented an important evolution in the methods of estimating migration flows from matrices of bilateral migrant stocks [101, 102, 103, 104].

On the other hand, there is a large variety of climate variables and indices that measure climate change effects. Most of the empirical studies, also for simplicity of interpretation, use temperature and precipitation as climate variables for linking migration and climate change [38, 39, 87, 105]. In many cases these variables enter the analysis explicitly, assuming or trying to capture a direct connection with migration. Considering the complex processes through

[5]Depending on the definition of the migrant stock, births would not influence the evolution of migrant stocks. Indeed, if migrants are considered by place of birth and residence, then a newborn to migrants would not enter their migrant stock but result as newborn in the natives' stock.

which climate change may result in migration decisions [8], and the broader demographic, political and economic context in which the affected population is embedded, it appears clear that these two variables alone can not give a comprehensive figure of climate change-induced international migration flows. On the other hand there is empirical evidence and agreement that climate change may act indirectly on migration through economic impacts [39, 88]. Recent studies have found robust evidence for the economic productivity to depend on climatic conditions in terms of precipitation and temperature [106, 107, 108, 109]. In line with these findings, global warming has been found of having increased global economic inequality [110]. Therefore, studying the impact of climate change on past and future migration through the indirect channel of macroeconomic impacts appears as a promising alternative for overcoming difficulties arising from both, assuming a direct relationship between climate variables and migration, and considering complex pathways of interactions.

1.3 Research questions and scope of the thesis

Climate change has affected and is projected to affect substantially natural and human-made systems. These impacts might disrupt the life conditions or expectations of people. In response to such events people could decide to migrate to another country. International migration is a powerful process that can transform both the origin and destination country through the transfer of cultural norms and economic capital, among others. Therefore, being able to estimate or make projections on how international migration patterns have reacted or will react to climate change is of relevant socio-political importance. Due to a paucity in migration data and to a complex interaction of environmental factors and socio-economic, demographic and political factors defining the migration decision, this objective is not easy to achieve. Moreover, methods that have been used in the past usually lack in accounting for important non-linearities and heterogeneities shaping the international migration process.

This doctoral research has aimed at (*i*) realizing a tool for estimating and projecting international migration flows, (*ii*) subsequently use it for attributing the role of climate change in spatial patterns of past migration flows and (*iii*) for quantifying the change of international migration patterns under future scenarios of global warming, considering different assumptions regarding the main macroeconomic channels of impact. The research has produced results that have been collected in three manuscripts, that are at the moment either published or under revision.

(*i*) Considering the limitations of previous international migration models and facilitated by a recently released global dataset of international bilateral migration flows, I have built a dynamic model of international migration addressing many of these limitations. The model, importantly, can distinguish between three different types of migration: emigration from county of birth, return and transit migration. This heterogeneity has been lacking in previous approaches that covered the entire globe. Moreover, it allows for including the important feedback effect produced by the diaspora at a higher resolution: a certain diaspora will attract only the population of same place of birth. Finally, in order to reach a more mechanistic approach the model includes for the first time, to my knowledge, important non-linear processes

shaping emigration rates in relation to economic parameters at the origin country, which would produce the highest rates of emigration from middle-income countries. The model, embedded within a dynamic population model which accounts also for changes in the population due to births and deaths, is validated on migration data covering an historical period. In a second step I have used it for producing projections of bilateral international migration under different socio-economic scenarios.
The results of this work have been published in :
Rikani A. and Schewe J. , *Global bilateral migration projections accounting for diasporas, transit and return flows, and poverty constraints.*, Demographic Research, 2021.

(*ii*) Climate change has manifested already globally, pervading both natural and human-made systems. In specific, its impacts might have already produced a substantial effect on international migration patterns. Climate change is likely to have produced an impact on the economic productivity of the countries. On the other hand, economic conditions at both origin and destination are recognised as important drivers of international migration. In order to circumvent the difficulties that could arise from a direct association between climate change and international migration I focus on this specific vector of impact transfer, while using two different methods for estimating the global warming impact on the economic productivity. The migration model developed in the first stage of the research has been used here for attributing the impact of climate change on recent international migration spatial patterns. I have produced estimates of migration under a counterfactual past without climate change. Results suggest that climate change has already had heterogeneous effects on international migration patterns, inhibiting flows from poor regions and inducing flows from richer regions. Overall, the counterfactual past without climate change would have seen less global migration moves.
The results of this attribution study are under revision for publication:
Rikani A., Otto C., Levermann A. and Schewe J., *More people too poor to move: Divergent effects of climate change on global migration patterns.*, Environmental Research Letters. Under revision.

(*iii*) Projections of increasing global warming pose an important question: how international migration patterns will react in response to future global warming impacts? In order to answer to this question I have used the indirect pathway of climate change impacts on the economic output of the countries. Focusing on a specific future global warming level and using two different methods for calculating the climate change impact on the economic productivity, I have produced scenarios of international migration under global warming. In order to use the migration model for projections, assumptions have to be made on how the influence of migration drivers observed for the past will change or hold in the future. Considering that the model is relatively simple and parsimonious in the number of explicit explanatory variables, the major source of uncertainty is identified by the non-linear relationship between emigration rates and income levels at the origin country. Some empirical results suggest that this relation might represent a pure spatial relationship, while other studies find that it actually represents a dynamic process that every country follows during its economic development. In my study I produce results for different assumptions regarding this process, including these two possibilities. Results suggest that global warming, acting through macroeconomic impacts, could have a significant effect on international migration patterns, under all the assumptions regarding the relation between emigration rates and income levels. Moreover, as for the case of past international migration, results show that it is important to go beyond figures of net change in migration flows and investigate both the flows that would be inhibited and those that would be induced

The results of this study are under revision for publication:

Rikani A., Frieler C. and Schewe J., *Climate change and international migration: Exploring the macroeconomic channel.*, PloS One. Under revision.

All these submitted articles have now been published in the respective journal.

2

Modelling international migration: the important role of the diaspora feedback, return and transit flows, and poverty constraints

Adapted from Rikani et al. "Global bilateral migration projections accounting for diasporas, transit and return flows, and poverty constraints. Demographic Research, 2021

2.1 Introduction

The estimated number of international migrants in 2020 amounted to more than 280 millions globally, proceeding in a positive trend since 1970, when the estimated number was less than 90 millions [1]. International migrants can have a powerful transforming effect, through the transfer of skills, money and cultural norms, not only on the country of destination but also on the country of origin (e.g. through remittances) [96, 2]. Therefore, being able to produce estimates of how migration flows will evolve in the future is of key socio-political interest. Different methods have been developed for producing estimates of future international migration flows. They have evolved during the last two decades, moving from predominantly deterministic approaches to probabilistic methods within the Bayesian probabilistic framework [111, 112, 113]. The latter, using historical data on migration, inform probabilistic futures where different uncertainties that shape migration flows are accounted for. However, these projections are produced without considering explicitly the role of migration drivers and therefore can not be used to investigate the impact that future changes of these drivers would have on migration.

Different from probabilistic forecasts, another stream of research has focused on constructing scenario-based projections of migration. In this case future trends of migration are produced by considering different assumptions on the drivers and processes of migration, therefore these approaches account directly for the effect of the change in drivers. Recently, a set of global migration projections have been produced within the context of the Shared Socioeconomic Pathways (SSP), which represent a set of storylines on future global socio-economic evolution [114]. Projections under SSP scenarios have been produced for important economic and demographic quantities such as Gross Domestic Product (GDP) and population [115, 116]. SSP-based migration projections, which are embedded within the population projections, assume a continuity with the past emigration and immigration rates for the first half of the current century and approach zero net migration at the end of century. Alternative scenarios of international migration have been produced by relaxing the zero net migration condition [117], or by coupling a migration model with a stylized model of the world economy [118].

The aim of the first part of my project has been to contribute to this second stream of research by producing projections of bilateral migration flows, explicitly depending on the major drivers of migration, and by investigating how changes of these drivers would affect migration patterns. The model that I present here explicitly accounts for the main drivers and processes shaping international migration flows but have been neglected in previous projections. As discussed in the introduction of this thesis, there is substantial agreement and corroborated empirical results in identifying the major drivers of international migration with: natural population change through births and deaths, average incomes in origin and destination country and the size of the diaspora in the destination country [18, 6, 119]. In particular, natural population change determines the size and composition of the population in a country and therefore the size and composition of population available to migrate. Incomes in the destination country represent a proxy for the expected economic gains from migrating to that country. The effect of income levels at the origin country are thought to have a non-linear dependence on emigration, which might arise from the superposition of two factors: desire to migrate and capability to afford migration. People with a lower income level would hypothetically have more incentives to migrate than those with a higher income. Indeed, the economic benefits would be higher for those with lower levels of income. On the other hand, if the person is too poor this might translate into a poverty constraint to migrating. The desire to migrate might follow an opposite path, being very high at the low levels of income and decreasing as the income level rises. Assuming a monotonous increase in the capabilities to migrate, as income rises, and at the same time a monotonous decrease of the desire to migrate, produces, in the superposition of these two processes, an inverse U-shaped relation between emigration and income levels, usually referred as the migration hump [6, 49, 44, 45] (Appendix, Figure A.1). Finally, migrant communities at the destination country (i.e. diaspora) are decisive in facilitating migration of new migrants from their country of origin [35, 119, 34]. They can provide economic and social help throughout the entire process of migration, reducing both the economic and social cost of migration. Thus it produces a positive feedback of self-amplification: all else being equal, larger diaspora in the destination country in a certain time produces a larger immigration flow, which translates into a larger size of diaspora at the end of the period of migration, and this larger diaspora will again attract a larger migration flow.

Whilst many empirical studies have confirmed the important role of these drivers in explaining past migration flows, they are rarely included in the methods used to project migration [118]. Nor do these methods account for the dynamic effect of the diaspora feedback on population's evolution. The non-linear effect of origin country income levels on emigration rates is also neglected in previous projections. Last but not least, existing projection methods do not differentiate between different types of migration such as transit and return flows. The latter can be large in some specific bilateral migration channels [103]. Therefore, not considering them separately would have a negative impact on projecting the evolution of migrant stocks.

In this first part of my work I will address these gaps by presenting a dynamic model of global bilateral migration that accounts for these mechanisms as well as for demographic and economic drivers. In specific, by defining each person by place of birth and place of residence the model can reproduce three different types of migration, including return and transit migration. I assume that the diaspora feedback depends on the place of birth rather than on the place of residence: migrants will be able to attract only people from the same place of birth. Emigration rates are also modelled assuming the desire-ability process described above: with emigration rates at very poor countries constrained at low levels, reaching a maximum in middle-income countries and decreasing again to a minimum in high-income countries, reproducing the migration hump function.

In the next section I will develop the migration model and calibrate it to the past levels of migration flows. I will then validate its performance on past international migration flows and I will produce migration projections under five different SSP scenarios.

2.2 Methods

2.2.1 The international migration model

I define the stock of population by place of birth and place of residence. This allows me to define a migration flow in a given period of time for each set of birthplace - origin (residence) - destination:

$$M_{k,i\to j} = a \cdot F(G_i) \cdot g_j^{\alpha_g} \, p_{k,j}^{\alpha_p} \, d_{ij}^{\alpha_d} \, P_{k,i}, \tag{2.1}$$

where $M_{k,i\to j}$ represents the number of people born in country k, residing in the country of origin i and migrating to the country of destination j, with $i \neq j$ and $k \neq j$. $P_{k,i}$ is the stock of population born in k and residing in i, also called diaspora of k in i and here represents the population at risk of migrating. When $k = i$ it defines the stock of natives of country i. $d_{ij} = d_{ji}$ is the geographical distance between i and j. $P_k = \sum_j P_{k,j}$ is the total population born in k and $p_{k,j} = P_{k,j}/P_k$ is the share of $P_{k,j}$ in the total population born in k. Turning to the economic variables, G_i is the Gross Domestic Product per capita (GDPc) of country i and $g_j = G_j/G_{glob}$ is the GDPc of the destination country j relative to the global mean GDPc, G_{glob}. Together with the α exponents the scaling factor a constitutes the set of parameters to be estimated.

Since $P_{k,i}$ represents the population available to migrate in the origin country and for that specific place of birth, the migration rate is defined as $m_{k,i\to j} = M_{k,i\to j}/P_{k,i}$. The relative diaspora term $p_{k,j}$ implies that migration increases with the relative size of the native population living abroad (for $\alpha_p > 0$). This also means that countries that have a larger share of the total diaspora of a certain country of birth, will attract more migrants of that same country of birth. In other words there is no interference between diasporas of different countries: the diaspora of country k, say residing in j, will affect only the flows of the population born in k, no matter where they reside.

The dependence of migration on origin income is complex and has been hypothesized to emerge from the interplay of capability and intention to migrate [26, 45]. I try to capture this behaviour with my model by using the superposition of two terms in defining $F(G_i)$. One term uses an hyperbolic function which starts with its maximum at low levels of income and decreases to a minimum value at high levels of income. This function is meant to describe the intention to migrate in terms of the levels of income at the origin. A second sigmoidal term, which starts with a minimum value at low income levels and rises to a maximum at high income values, is meant to describe the capability to migrate in terms of the income levels at the origin, i.e. to economically finance migration. The superposition of these two terms assumes the following form:

$$F(G_i) = F_{intent}(G_i) \cdot F_{resource}(G_i) = \frac{1}{1 + \dfrac{G_i}{\widehat{G}}} \cdot \frac{1}{1 + e^{-\gamma(G_i - \tilde{G})}}, \tag{2.2}$$

which describes a hump-shaped relation between emigration rates and origin GDPc, conditional on the parameters $\widehat{G}$ and $\tilde{G}$ (Figure 2.1, inset).

The three dimensions (place of birth, origin and destination) that I use for defining the migration flow, allow for distinguishing between three type of migration: (i) emigration from country of birth (CoB); (ii) transit migration between countries different from the CoB; (iii) return migration to the CoB. From Equation 2.1, when $k = i$, the migration flow represents the emigration of people from their country of birth. I assume that transit migration, for $k \neq i$ and $k \neq j$, is described by the same Equation 2.1. This means that a migrant born in country k and residing in country i can decide to migrate to a third country j driven by the same factors as the natives in country i. This also assumes that the migrants face the same financial constraint as the natives. The assumption ignores though that migrants often tend to have lower incomes than the natives and therefore the intention and capability to migrate might not correspond to the same level as for natives.

Finally, for the return migration I simply assume that it depends on distance and population available to migrate, which is the diaspora of the destination country living in the origin country:

$$M_{j,i \to j} = b \cdot d_{ij}^{\beta_d} \, P_{j,i}. \tag{2.3}$$

This assumption, while simplistic, can be justified by previous empirical findings. A strong proportionality has been observed between return flows and diaspora size [103, 104] (see also Appendix, Figure A.2), while previous findings also suggest that economic factors might have only a small influence on return migration [120, 121]. Again, b and β_d are parameters to be estimated.

The dynamic simulation consists in calculating all the bilateral flows[1] for a certain period $[t, t+\Delta t]$, where t is the initial year of the period, Δt is the time step of my simulation and defines the extension of the period. After calculating all the bilateral flows, all population stocks are simultaneously updated by adding the net migration flows:

$$\tilde{P}_{k,i}(t) = P_{k,i}(t) - \sum_{l \neq i} M_{k,i \to l}(t) + \sum_{l \neq i} M_{k,l \to i}(t). \tag{2.4}$$

$P_{k,i}(t)$ is the population stock at the beginning of the period, $\sum_{l \neq i} M_{k,i \to l}(t)$ and $\sum_{l \neq i} M_{k,l \to i}(t)$ are the total emigration and immigration flows, respectively, for the specific $P_{k,i}$ population stock. Migration flows are calculated by using Equations 2.1 and 2.3, where all the variables are evaluated at time t. $\tilde{P}_{k,i}(t)$ represents the updated stock of population. In order to have a complete process of population evolution, natural population change due to births and deaths is also accounted for in the model. Population stocks, updated by the net migration flows, are then updated by births and deaths by using country-specific fertility and mortality rates, $r^{\star}$ and $r^{\dagger}$, respectively. By definition, the children born to the diaspora enter the stock of natives. The temporal evolution of each population stock is therefore fully described by the following equation:

$$P_{k,i}(t) = \begin{cases} \tilde{P}_{k,i}(t) \cdot (1 - r^{\dagger}_k(t)), & k \neq i \\ \tilde{P}_{i,i}(t) \cdot (1 + r^{\star}_i(t) - r^{\dagger}_i(t)) + \sum_{l \neq i} \tilde{P}_{l,i}(t) \cdot r^{\star}_l(t) & k = i. \end{cases} \tag{2.5}$$

Both mortality and fertility rates are expressed per model time step. Diasporas are given the same fertility and mortality rates of their country of birth. This is a strong assumption compared to the complex behaviour defining the patterns of natural change rates of migrants. For example, due to age-specific self-selection of migration, diasporas may have a lower rate of mortality and larger rate of fertility than population at both destination and country of birth. Skill-specific selection might also lead to lower rates of fertility in the diaspora compared to those in the country of birth [122]. This heterogeneity in fertility rates of migrants has emerged also from a recent study where a large dataset of both high income and developing countries was used. Results suggested an almost equal share of cases with higher and lower fertility rates among migrants, compared to the rates in the origin country [4]. Despite the complexity defining fertility rates among migrants, many empirical results suggest that fertility of diasporas differs strongly by country of birth [123, 124, 125]. Relying on this empirical result and being aware of the more complex nature of the natural change of immigrant populations, I assume that diasporas' natural evolution follows that of the country of birth. This assumption also produces total population changes more in line with the observed one, compared to the case where diasporas assume the natural change rates of the country of residence (Appendix, Figure A.3)

Using a five-year step, I iteratively evaluate the temporal evolution of the population stocks using Equation 2.5. In this sense I simulate the evolution of directed migration flows defined by origin, place of birth and destination. This dynamic simulation covers 177 countries or

[1] Following the definition of the migration flows this is a three dimensional matrix.

territories while other 44 mainly small countries or territories are excluded due to missing GDPc data (Appendix section A.1).

2.2.2 Data

I use data on historical bilateral migrant stocks [126] and country-level total population [127] coming from the Population Division of the United Nations (UN) Department of Economic and Social Affairs (DESA). The source for the historical country-level GDP is the Penn World Table (PWT) release 8.1 [128]. GDP data are reported in terms of 2005 purchasing power parity (PPP), and are therefore consistent with the projected GDP data from the SSP scenarios. Missing data for some countries are taken from the release 9.0 of the PWT, after rescaling from 2011 to 2005 PPP [129]. Data on geographical distance between countries is taken from CEPII [130].

Historical migration data comes from a recently produced global matrix of bilateral migration flows [104]. This dataset covers the period from 1990 to 2015 on five-year intervals. Migration flows were derived using a pseudo-Bayesian approach on population stocks matrices in two consecutive time points [103]. Hereafter, I refer to this migration flows dataset as A19. The major benefit of using this dataset, compared to other migration flows dataset, is the geographical coverage, not restricted to developed countries or specific regions [98]. The underlying population stock data from which the migration flows are derived in A19, includes, when reported by the countries, refugees population. It means that in general, the migration flows in A19 do also include refugee flows. In an attempt to remove refugee flows from the A19 data I have used bilateral refugee stocks data from the UN High Commissioner for Refugees (UNHCR), as well as data on naturalization of refugees [131].

Historical values for the variables governing the natural population change, i.e. fertility and mortality rates, are obtained from the UN DESA [127]. Projected values of these variables come from the zero-migration variant of the projections.

Data on future country-level GDP come from the long-term macroeconomic projections produced by the OECD within the SSP framework [115]. Each SSP defines qualitatively a potential future in terms of societal, political and economic changes, among others [114, 132]. The initially qualitative formulation of these potential futures was translated then into quantitative assumptions of key drivers of economic and population growth, ultimately producing country-level GDP and population trajectories, from which GDPc trajectories are calculated[2] [116, 115]. Differentiated by the assumptions on the drivers, these trajectories allow for exploring the potential effects of different development trajectories on international migration patterns.

2.2.3 Fitting procedure

In order to estimate the parameters of Equations 2.1, 2.2 and 2.3, I proceed in two steps, using a Nonlinear Least Squares method.

In the first step I estimate the parameters of Equation 2.2, which describes the migration hump relation between emigration rates and GDPc for a certain country. To this end I

[2] A comprehensive description of the assumptions regarding each scenarios can be found in the introduction of this thesis or at the original manuscript [114].

proceed with excluding refugee flows and return flows from the original matrix, $\hat{\mathbf{M}}_{i \to j}$, of global bilateral flows reported in A19. It is worth mentioning that flows in A19 are reported only by country of origin and country of destination, and do not explicate the country of birth. This preliminary step is necessary because my Equation 2.2 is not a good representation of refugee flows and furthermore is assumed not to hold for return flows (see Equation 2.3). I estimate the refugee flows as the difference of refugee stocks in two consecutive periods, accounting also for naturalization and natural population change. Since the data on bilateral refugee stocks is reported by country of origin, rather than country of birth or citizenship, I can estimate bilateral flows only by origin and destination without specifying the country of birth. I calculate the refugee migration flow from country i to country j at time t as follows,

$$\hat{M}^{rfg}_{i \to j}(t) = P^{rfg}_{i,j}(t+1) - P^{rfg}_{i,j}(t) \cdot (1 + r^{\star}_i(t) - r^{\dagger}_i(t)) + N^{rfg}_{i,j}(t), \tag{2.6}$$

where $P^{rfg}_{i,j}$ represents the refugee population of origin i residing in country j, and $N^{rfg}_{i,j}$ is the number of refugees naturalized during the five-year period. When $M^{rfg}_{i \to j}$ is negative, I assume its absolute value to be a flow in the other direction, i.e. from j to i. This process produces a new matrix of global migration bilateral flows $\hat{\mathbf{M}}^{norfg}_{i \to j}$, where the refugee flows are excluded from the original matrix:

$$\hat{M}^{norfg}_{i \to j} = \hat{M}_{i \to j} - max(0, \hat{M}^{rfg}_{i \to j}) - min(0, \hat{M}^{rfg}_{j \to i}). \tag{2.7}$$

After removing the refugee flows I proceed with removing the return flows. Since the flows in A19 do not report the country of birth I can not proceed with explicitly excluding them. Therefore, I assume that bilateral flows where the country of origin is more than twice as rich as the destination country, in terms of GDPc, consist mainly of return flows. This is not a precise filter, but it does remove some of the most important routes of return migration, such as from the Gulf States to South Asia and from the USA to Mexico, while preserving a large part of migration flows (Appendix, Table A.1 and Figure A.4). After different tests it also appears clear that the exact choice of this threshold does not have much influence on the shape of the estimated function (Appendix, Figure A.5).

Then, since the migration hump function is a relation between GDPc and total emigration rate of the country, I aggregate the bilateral flows to obtain total relative emigration flows. The fit of Equation 2.2 on total relative emigration flows reads as follows:

$$\sum_{l \neq i} \hat{m}^{norfg}_{i \to l} \approx a_e \cdot F(G_i) = a_e \cdot \frac{1}{1 + \dfrac{G_i}{\widehat{G}}} \frac{1}{1 + e^{-\gamma(G_i - \tilde{G})}}. \tag{2.8}$$

After estimating the parameters in Equation 2.2 I proceed with estimating the remaining parameters in Equations 2.1 and 2.3. In this case I use the original A19 dataset of bilateral migration flows, without excluding refugee or return flows. Since the data from A19 is aggregated on the place of birth dimension, these flows would be comparable to the sum of the three migration types defined in the model, i.e. emigration from CoB, transit and return migration. To simplify the computation I fit the observed flows from A19 to only the sum of emigration from CoB and return flow. This procedure neglects the transit flows, which constitute 9% of the global flows [103]. Still, it is more detailed than previous studies where are used mainly emigration flows from sending countries [119, 133]. The fitting equation in this case reads as follows:

$$\hat{M}_{i\to j} \approx M_{i,i\to j} + M_{j,i\to j} \approx a \cdot F(G_i) \cdot g_j^{\alpha_g}\, p_{i,j}^{\alpha_p}\, d_{ij}^{\alpha_d}\, P_{i,i} + b \cdot d_{ij}^{\beta_d}\, P_{j,i}, \tag{2.9}$$

where the function $F(G_i)$ is evaluated using the estimates from the previous fit.

Along with this method of estimation of the parameters I run, as a robustness test, a second estimation using an alternative migration flow dataset. I obtain this new dataset by using a simple stock-differencing method, augmented by accounting for changes due to deaths: $\Delta P_{i,j}(t) = P_{i,j}(t+1) - P_{i,j}(t) \cdot (1 - r_i^{\dagger})$. Following the previous estimation method, I neglect the transit flows and, approaching a stock-differencing reverse negative method [104], I assume that an increase in migrant stock is due to immigration, while a decrease is due to return migration:

$$\Delta P_{i,j} = \begin{cases} a \cdot F(G_i) \cdot g_j^{\alpha_g}\, p_{i,j}^{\alpha_p}\, d_{ij}^{\alpha_d}\, P_{i,i} & \text{if } \Delta P_{i,j} > 0 \\ -b \cdot d_{i,j}^{\beta_d}\, P_{i,j} & \text{if } \Delta P_{i,j} < 0. \end{cases} \tag{2.10}$$

This method of estimation suffers from two main issues: the first is related to the large amount of not reported bilateral stocks in the source data[3], the second is related to the assumption that a change in the bilateral stock may be due to either immigration or return, but not a combination of both of them. Therefore the estimation of the parameters using this alternative dataset is to be considered only as a robustness test.

Because the traditional gravity model used in empirical studies is log-linear, this has resulted in many cases in using a simple linear regression (after log-transforming the migration model) for estimating the parameters. Given the relatively more complex form of my migration model, due to the migration hump function $F(G_i)$ and the different types of migration, a linearisation of the model by a logarithmic transformation is not possible. Therefore I use Nonlinear Least Squares to estimate the original, not transformed, model. Besides this technical constraint, using the untransformed model circumvents problems that might arise in the presence of zero values, at either dependent (flows) or independent (diaspora) variables. Excluding these cases might lead to biased estimates when considering a log-transformed gravity model [134].

2.3 Results

2.3.1 Estimation results

The estimated model achieves an R^2 of 0.73, a high explanatory power considering that the model does not account for any unobserved idiosyncrasies of individual migration flows. The estimated parameters are in line with previous analysis and consistent with the expected values (Table 2.1). The diaspora size positively associates with the size of the flows, in line with the positive self-amplifying feedback process hypothesized at the beginning. Bilateral migration flows are also positively associated with the relative GDPc at the destination.

[3] Many blateral migrant stocks are not reported separately but included in aggregated categories such as Global North and Global South.

Table 2.1: Estimated values for the migration model, with (main) and without the distance variable (no distance), in both cases using the migration flow dataset from A19. Estimates obtained using the alternative dataset of migration flows obtained through a stock-differencing method are reported in the right-end column (stock difference). Values used for the dynamic simulations are shown in bold. Error margins refer to the 99% confidence interval. Origin GDPc parameters are estimated separately, in the first step as described in the methods. GDPc values are real GDPc in thousand US dollars at 2005 PPP.

Variable		Estimation method		
		main	no distance	stock difference
Emigration from CoB and transit migration				
Intercept	a	0.153 ± 0.009	**0.270** ± 0.004	0.26 ± 0.04
Diaspora	α_p	0.956 ± 0.003	**0.946** ± 0.003	0.952 ± 0.008
Destination GDPc	α_g	0.226 ± 0.008	**0.252** ± 0.007	0.70 ± 0.04
Distance	α_d	0.079 ± 0.008	**0**	-0.10 ± 0.02
Origin GDPc	γ	**-0.0015** ± 0.0009		
	$\widehat{G}$	k$ **22.6** ± 17.2		
	$\tilde{G}$	k$ **1.2** ± 0.4		
Return migration				
Intercept	b	0.20 ± 0.02	**0.127**± 0.001	153± 51
Distance	β_d	-0.06± 0.01	**0**	-1.02 ± 0.05
Data points	N	166530	166530	40462 (emigration) 8361 (return)
Coefficient of determination	R^2	0.73	0.73	0.46 (emigration) 0.36 (return)

The estimated parameters of the non-linear function related to the origin GDPc, produce a hump-shaped function with the peak of emigration rates at approximately 3500 US Dollars of GDPc (Figure 2.1). This is comparable to values found previously using a non-parametric regression approach [44]. This result is corroborated by a non-parametric analysis on the same dataset (Appendix, Figure A.1), showing that the estimated function is an adequate representation of the empirical observations.

The effect of geographical distance on migration flows appears small and inconsistent (i.e. positive effect). A plausible explanation would be that the diaspora and destination GDPc are much more important drivers for the choice of the destination country. Moreover, the diaspora variable might reduce the costs of migration and therefore reduce the impact of the distance on migration. A smaller coefficient for the distance variable is also in line with recent results from the gravity models of trade, estimated on untransformed models instead of their log-transformed version [134, 135]. Indeed, when I estimate the log-transformed version of the model the effect of distance turns negative and larger. When I use the alternative flow dataset, obtained through a stock differencing method, the model's performance is lower in terms of R^2 (Table 2.1, stock difference column). The reasons might be multiple, for example the much smaller sample size, due to many bilateral stocks not being reported individually, might result in a biased dataset of flows. A second motivation would be related to the relatively "crude" method of estimating the flows from the stocks, compared to the demographic accounting

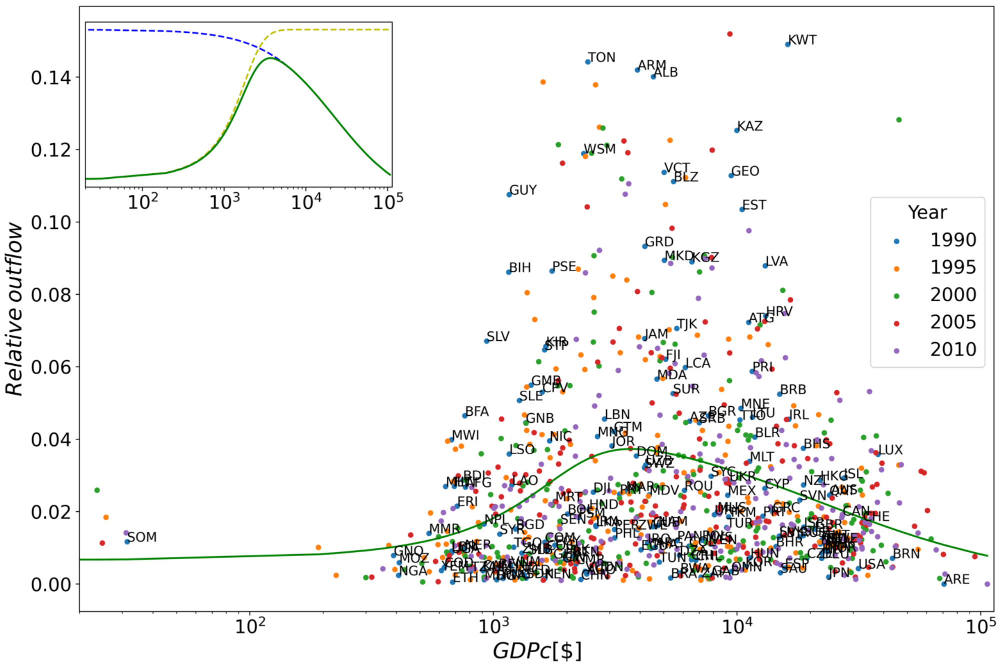


Figure 2.1: Result from the fit of Equation 2.2. Each dot represents a country with its total emigration rate and GDPc level, for each of the five-year periods. Country's ISO code is reported for the data points in 1990. The green line is the fit of Equation 2.2 to the data (estimates are given in Table 2.1). The inset illustrates, for an arbitrary y scale, the two components of Equation 2.2 and their superposition.

method used in A19. Besides the R^2 value, this alternative estimation produces a similar value for the diaspora coefficient and negative stronger effect of the distance. The destination country GDPc coefficient is also larger than the one estimated using the A19 dataset. This result may be explained by the selection on migration flows imposed by the reduced number of flows obtained from the stocks. Indeed, this incomplete sample is biased towards middle- and high-income destination countries (Appendix, Figure A.6)

Since the effect of the distance on the bilateral migration flows is small and inconsistent, I choose to reduce the final version of the model by effectively removing the distance as explanatory variable of the model. The fit of the new, reduced, model yields equally high explanatory power and similar values of the estimates (Table 2.1, middle column). This is the version of the model used to perform dynamical simulations. In order to account for the uncertainties resulting from the estimation method I also provide simulations using the upper and lower bounds of the 66% confidence interval for $\widehat{G}$, which is the parameter that characterizes the dependence of migration intent on the origin GDPc. The uncertainty on this parameter produces the largest effect on simulated migration flows for both periods of interest, past and futures under the SSP scenarios (Appendix, Figures A.7 and A.8).

2.3.2 Migration trends: Reproducing the past

In this first analysis the dynamic model is initialized at the year 1990 with historical bilateral migrant stocks [136] and GDPc [128]. It is run then until 2015, with the historical GDPc values entering the model as external forcing quantities. At the end of the simulated period the total migrant stocks are still highly correlated (Figure 2.2).

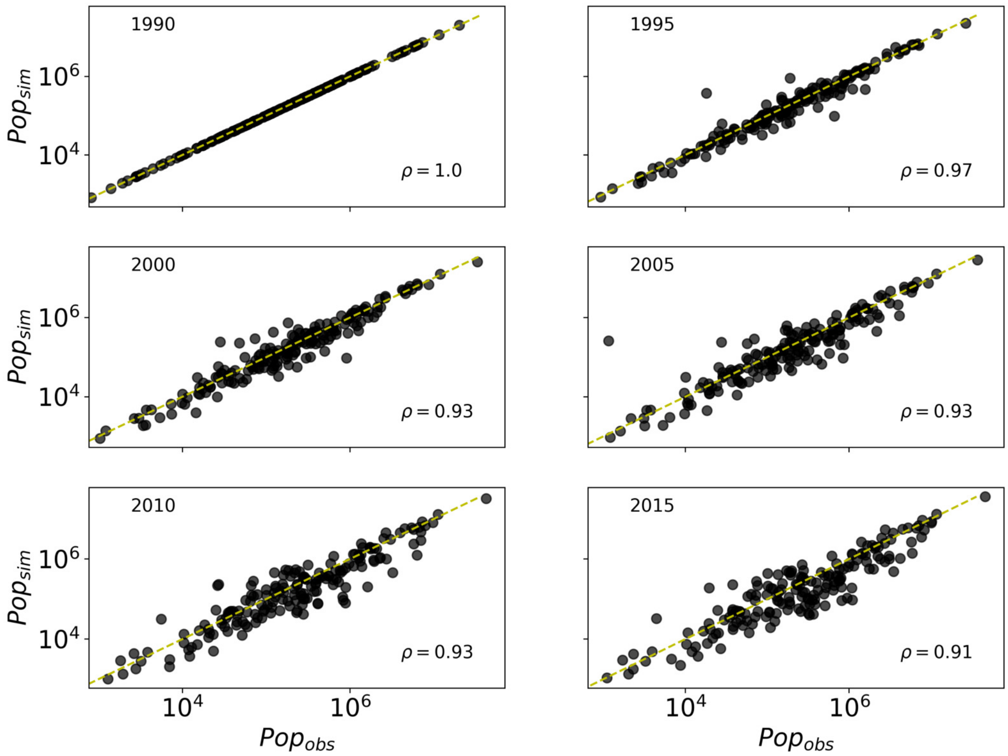


Figure 2.2: Simulated against observed migrant stocks per residence country. The Pearson correlation coefficient is reported for each five-year interval within the historical period. The dashed line represents the identity line.

Concerning the migration flow, globally it is simulated to increase at a rate similar to the observed one from the A19 dataset (Figure 2.3, black and green dashed line). On the other hand, its simulated level is lower than the observed one. A possible explanation can be the refugee flows, which are included in the A19 flows but not accounted for in my model. Indeed, results get closer to the observed ones when I try to exclude the refugee flows (Figure 2.3, black and solid green line). Still, the method I used for excluding the refugee flows from the original A19 dataset is likely not capable of capturing properly all refugee flows.

Besides the simulation using the historical GDPc forcing on migration, I produce a counterfactual simulation, where the GDPc is held constant, at its initial value, during the entire period of simulation. This simulation produces very similar levels of global migration flow (black dotted lines in Figure 2.3). Considering the strong effect of the GDPc at the origin country this result is surprising or at least not trivial. It suggests that, despite the reduction in global economic inequality[4], which may have reduced migration, the economic development experienced by the less developed countries has led to increasing emigration rates, counterbalancing the first effect. The result also suggests that the inertia of the diaspora feedback strongly defines the migration flows.

[4] The between-country Gini coefficient has dropped from 0.75 to 0.65 during the period of observation [115].

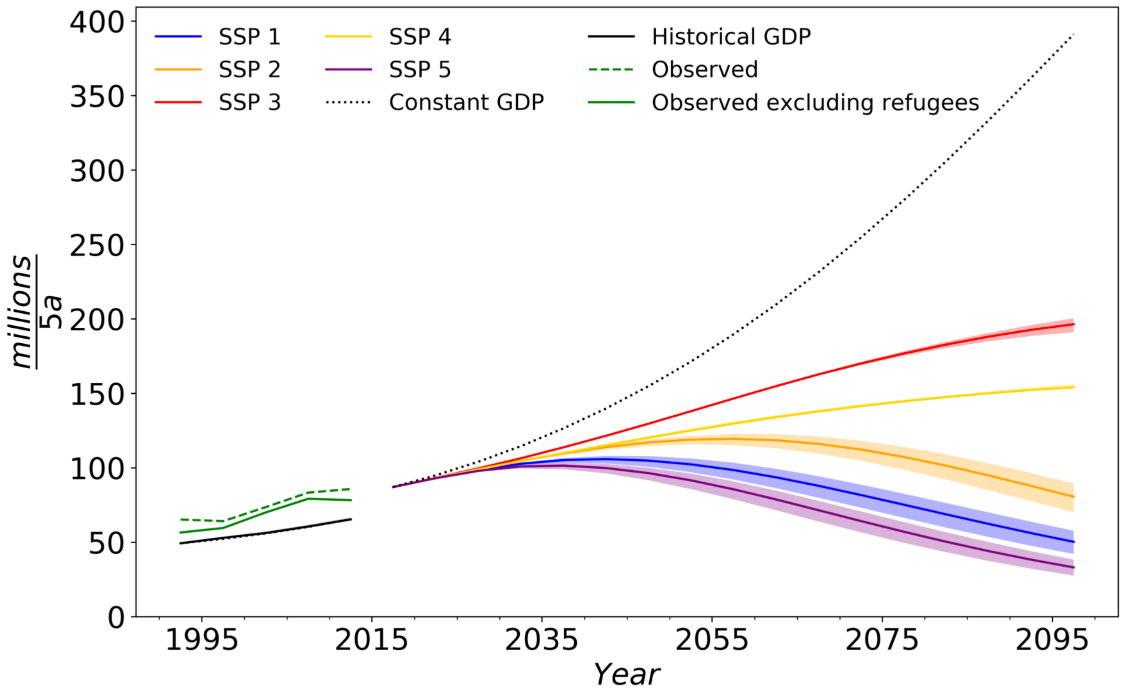


Figure 2.3: Global migration flow evolution. Green dashed line represents A19 data; the same but excluding the refugee flows is reported in the green solid line. Black solid line shows the evolution for the historical period, using historical GDPc values. The counterfactual simulations where the GDPc is held constant are shown in black dotted lines (for the historical and projection period). The other coloured solid lines show the evolution of global migratin flow under the five SSP scenarios. The shading around the simulations with varying GDPc represents the simulation of the model using the upper and lower bound of the 66% confidence interval for the most uncertain parameter, $\widehat{G}$.

At a higher resolution, I focus on net migration flows at the regional and country level. Following the definition in A19 , I consider ten major world regions. Results show that the model approximately captures the level[5] of net migration for most of the regions and large emigration and immigration countries (Figures 2.4–2.6, and for all the remaining countries Figures A.9–A.15). The long-term trends in net migration are also captured for many regions and countries: rising net immigration into Europe, Oceania and West Asia, and rising net emigration from Africa and South, Southeast and East Asia.

The counterfactual simulation with the GDPc held fixed at the initial value shows monotonic increase in the size of net migration for almost all regions and countries. As observed earlier, this counterfactual simulation highlights the strong impact of the positive feedback produced by the diaspora. By comparing this simulation to the baseline run, where the GDPc entering the simulation assumes the historical values, I can study the effect of the economic development on net migration flows. The differences become substantial after the year 2000, suggesting that changes in GDPc have, on one hand, reduced net emigration from East Asia and Latin America, and on the other hand have increased immigration into Europe and West Asia.

As already pointed out above, the simulation does not capture many of the short-term variations in migration flows. These variations may be caused by refugee flows as well as by

[5]The model is not capable of capturing the short-term variation in migration but the level simulated lies, in many cases, within the variability of the observed flows.

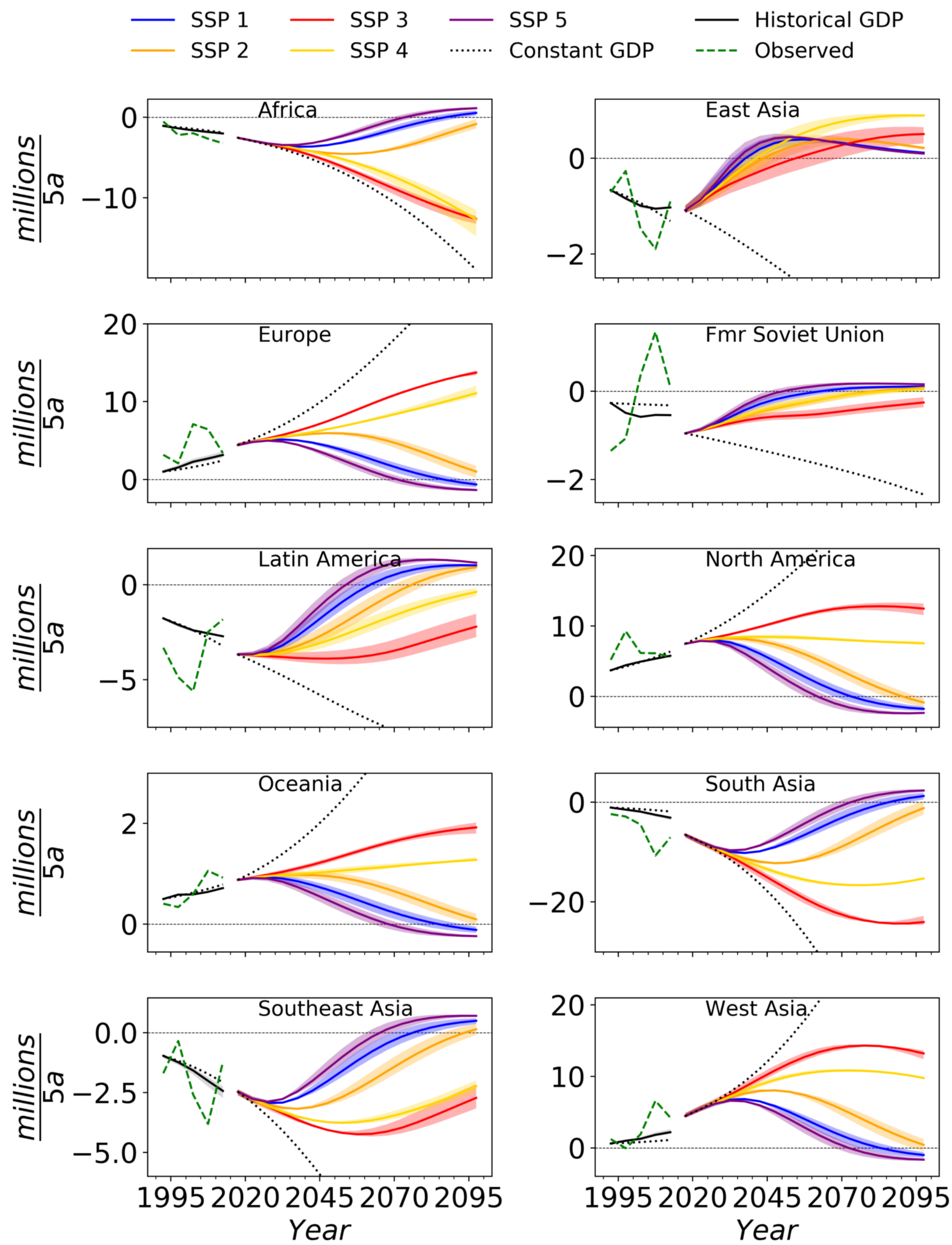


Figure 2.4: As in Figure 2.3 but for net migration in ten world regions. Positive net migration means more immigration than emigration.

other factors not included in my model. For instance, immigration policies are not included in the model and major economic and geopolitical events such as global financial crisis or dissolution of large countries are also events that show their effect on migration in the observed (A19) data but are not captured in my model. For example, large flows are observed between countries of the former Soviet Union after the collapse in 1990. The sudden appearance of large diasporas in these new countries produces, through the positive feedback, a lasting effect on migration flows. Also, following the war in Syria, huge migration flows are observed from Syria and Turkey after the year 2011 (Figure 2.6). All these are examples of flows that the model does not and can not capture. Increasing the resolution of analysis of the results, simulated bilateral flows show the same limitations as the net migration flows: a good match of the

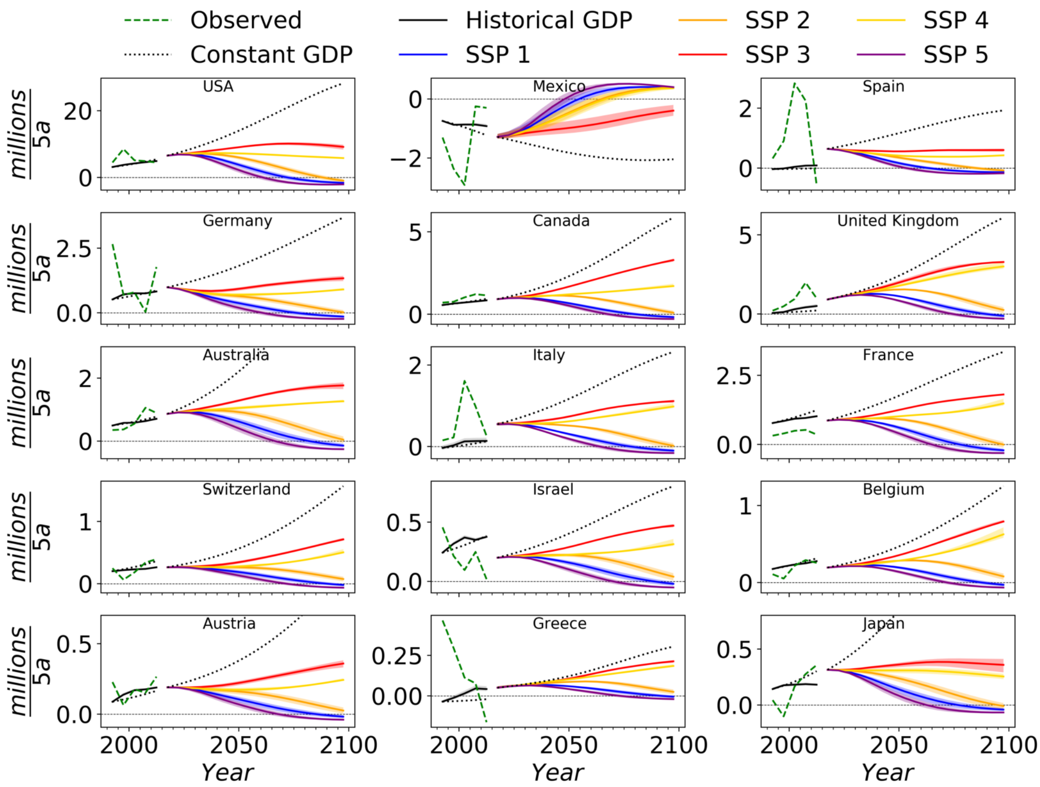


Figure 2.5: As in Figure 2.4 but for net migration in a subset of OECD countries. Countries are sorted in descending order by their average historical net migration count, excluding refugees.

level and long-term trend but difficulties in capturing the short-term variations (Figures 2.7 and 2.8). By exploiting fully the resolution power of the model, I can analyse the role of the different types of migration: emigration from CoB, transit and return migration. As expected, emigration from CoB is the largest component of the total flow for most of the large bilateral channels. Confirming previous studies, return migration appears as an important component for many bilateral channels, such as Russia-Ukraine and India-Pakistan. In others, like USA to Mexico and India to Bangladesh, it becomes the largest component of the total flow. Transit flows, even if bring a smaller contribute to the total flow, are not negligible, especially in regions like the Balkans, former Soviet Union and Middle East (Figure 2.9). These are regions that include countries with a large share of diaspora from other countries in the same region (for example countries of the former Soviet Union or countries of ex-Jugoslavia).

2.3.3 Migration trends: projecting the future

The second part of the results focuses on projections of bilateral migration flows. The simulation is initialized with observed data on population stocks in 2015 and SSP-based GDPc in the same year. These stocks differ from those obtained as the result of the previous dynamical simulation. Therefore is not surprising to have a gap between the level of the last simulated flow from the historical run, and the first simulated flow from the projection run. A large gap in the flows corresponds to a large discontinuity between the observed population stocks and the simulated ones from the historical run.

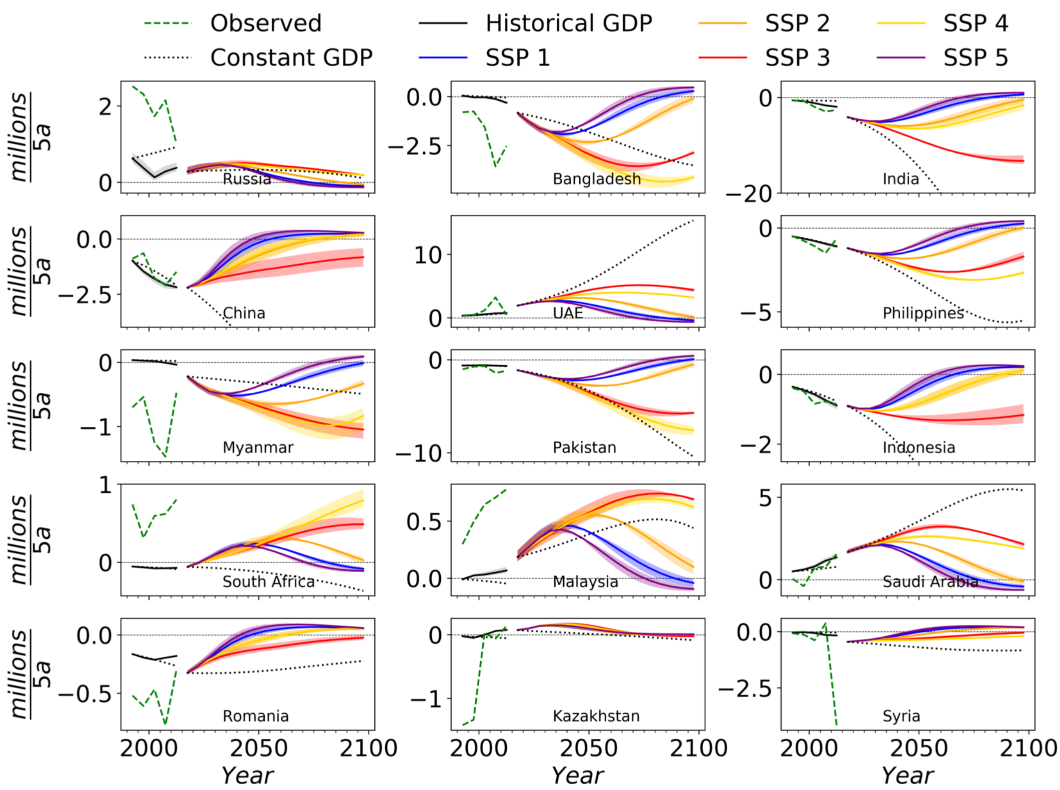


Figure 2.6: As in Figure 2.5 but for net migration in a subset of non-OECD countries.

Initialized with population stocks and GDPc data on the year 2015 the model runs until the end of the century (2100), following the projected GDPc under the five SSPs [115] and the projected natural population change from the UN DESA [127], under the zero-migration variant. Similar to the historical run, I also produce a counterfactual simulation where the GDPc is held constant on its initial value in the year 2015, throughout the entire period of simulation. This counterfactual case shows a continuous monotonic increase in net migration during the entire period of simulation, for all regions and most large countries (Figures 2.4–2.6).

Diverging from this pattern, the simulations under the different SSP scenarios lead to, in absolute terms, lower levels of net migration flows (Figure 2.4). The differences are substantial also between SSP scenarios. Under medium and rapid economic growth scenarios, like SSP 1 and SSP 5, net migration flows are projected to approach zero by the end of century for all regions and for many countries. The same is observed for SSP 2, even though it happens at a slower pace. Conversely, under SSP 3 and 4, net migration flows keep rising throughout the century in Europe, Oceania and Africa. In other regions like Latin America, Southeast and West Asia net migration flows reach a peak around the year 2060 and start decreasing from thenceforth. This turning point is reached later in North America and is approached only at the end of the century in South Asia. Under both SSP 3 and 4, East Asia turns from a net *emigration* to a net *immigration* region after the mid-century and migration keeps increasing in absolute terms while approaching the end of the century. Contributing substantially to this result are countries like China and Japan which see, at the end of the century, low levels of emigration and high levels of immigration, respectively. Former Soviet Union is the only region where, under all the SSP scenarios, net migration approaches zero at the end of the century.

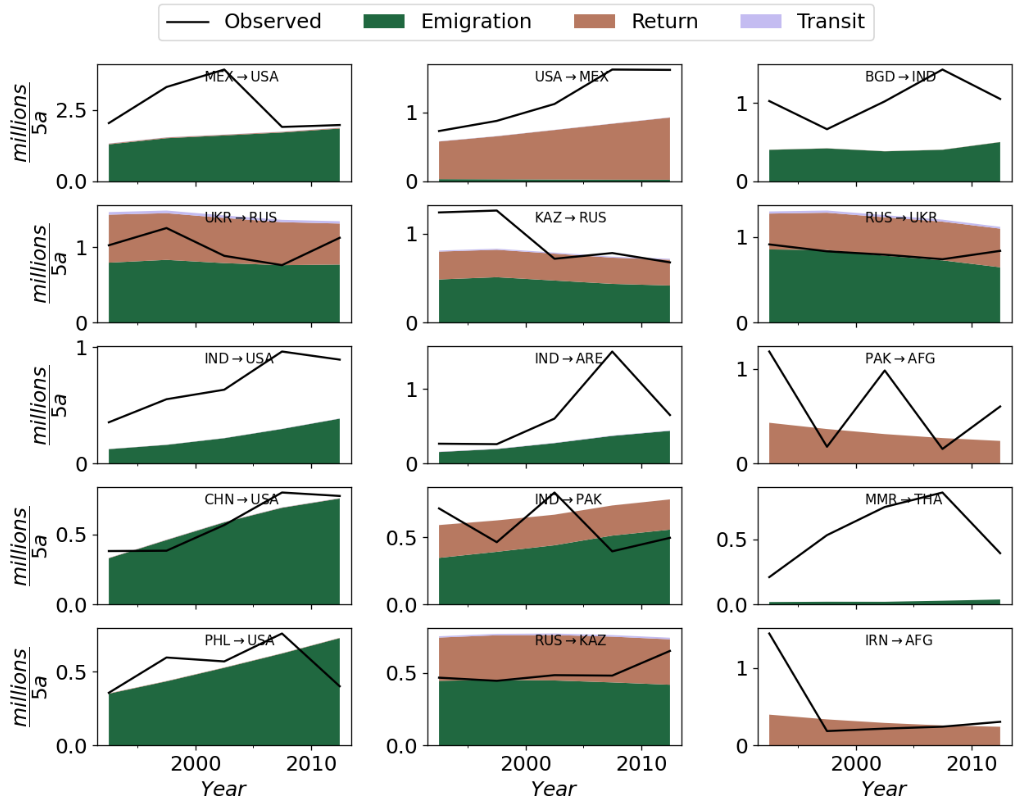


Figure 2.7: Bilateral migration flows, in descending order by their average observed flow. Black lines show observed flows (A19), while colors show the levels reached in the simulation by the three different migration types (emigration from CoB, return, transit). These three type of flows are stacked on top of each other and the upper end of the coloured area represents the simulated total flow.

These patterns are observed also when I disaggregate the flows at the country level (Figures 2.5 and 2.6). In particular, countries like Bangladesh and Myanmar show an interesting dynamics that diverges from that observed in many other countries: during the initial period of simulation net migration flows under all SSP scenarios are higher than compared to the counterfactual case of constant GDPc. This means that for these countries, as the GDPc rises, emigration flows increase substantially, according to Equation 2.2, suggesting that poverty constraint on emigration plays a fundamental role in these cases. Later on, as the GDPc keeps rising, net migration in these countries peaks and starts decreasing, tracing the migration hump. The timing of tracing the migration hump differs between the SSPs: for SSP 1, 5 and 2 the economic growth is faster than in SSP 3 and 4, and the peak is reached earlier. The same dynamics but for net immigration is observed for Malaysia and South Africa, suggesting a migration hump path of emigration in those countries that mainly contribute to immigration into Malaysia and South Africa.

An interesting aspect of the dynamics of the model is the way countries approach net zero migration. They cross the zero, going from being net immigration countries to net emigration and vice versa. This behaviour is explained by the fact that, for a given pair of countries, the flow of return migration reaches its peak after the flow of migration from CoB reaches its own. When the latter has reached its maximum the migrant stocks are still large enough to produce

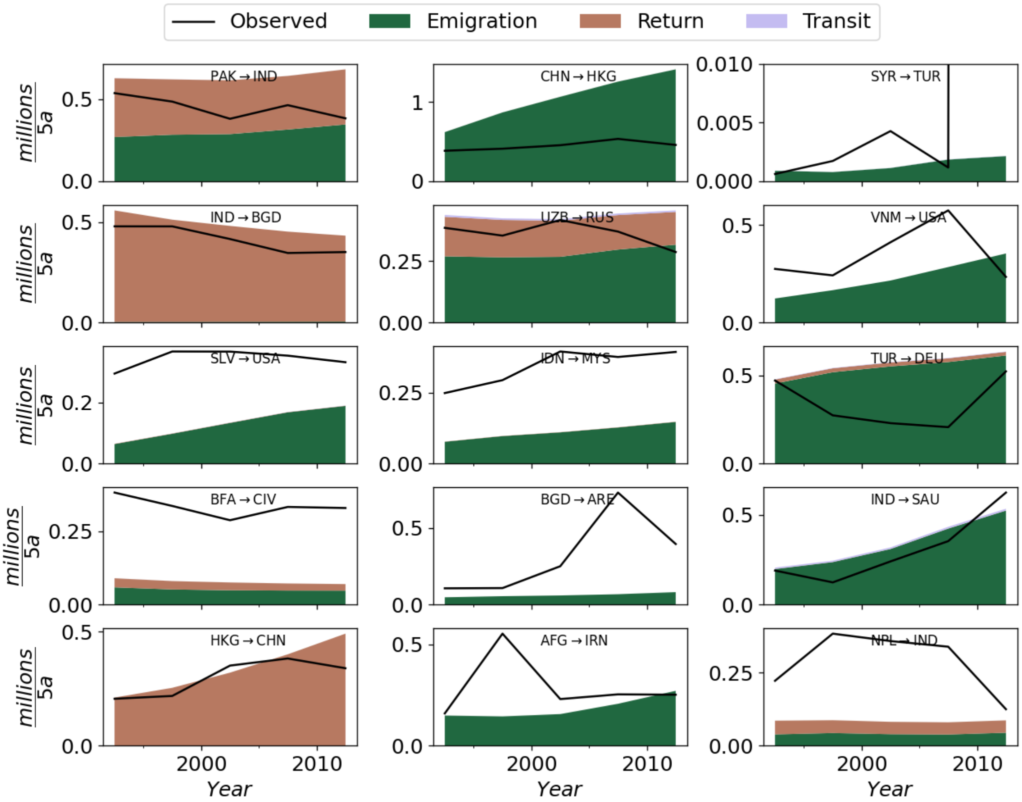


Figure 2.8: As in Figure 2.7 but for other bilateral flows.

a return flow larger than the migration from CoB, producing the change in the sign of net migration (Appendix, Figures A.16 and A.17).

The uncertainties coming from the estimation of the model's parameters become not negligible in the set of projection simulations (Figures 2.4– 2.6, shading). This uncertainty assumes a substantial magnitude under SSP 3 and for some regions and countries the spread of the results due to different values assumed for the parameters can be comparable to the simulated migration flow itself. Nonetheless, the spread of the results under different SSPs still dominates the total spread of the projections, allowing for a proper interpretation of the results related to the different assumptions on the GDPc projections.

2.4 Discussion

Keeping in mind the differences between the SSPs scenarios in terms of GDPc evolution and between countries inequality [115], I can discuss the results and suggest an interpretation in line with these differences. Indeed, my projections highlight the important role of different assumptions embedded in the SSP projections of GDPc in shaping the evolution of international migration patterns. For instance, SSP 3 describes a future defined by regional rivalry and stagnant economy: the model projects large and persistent net migration flows from the Global South to Global North and Gulf States. On the other hand, in more optimistic scenarios, like SSP 1 and 5, poor countries follow a relatively fast development transition, overcoming potential poverty constraint to migrating. Consequently the model produces rising

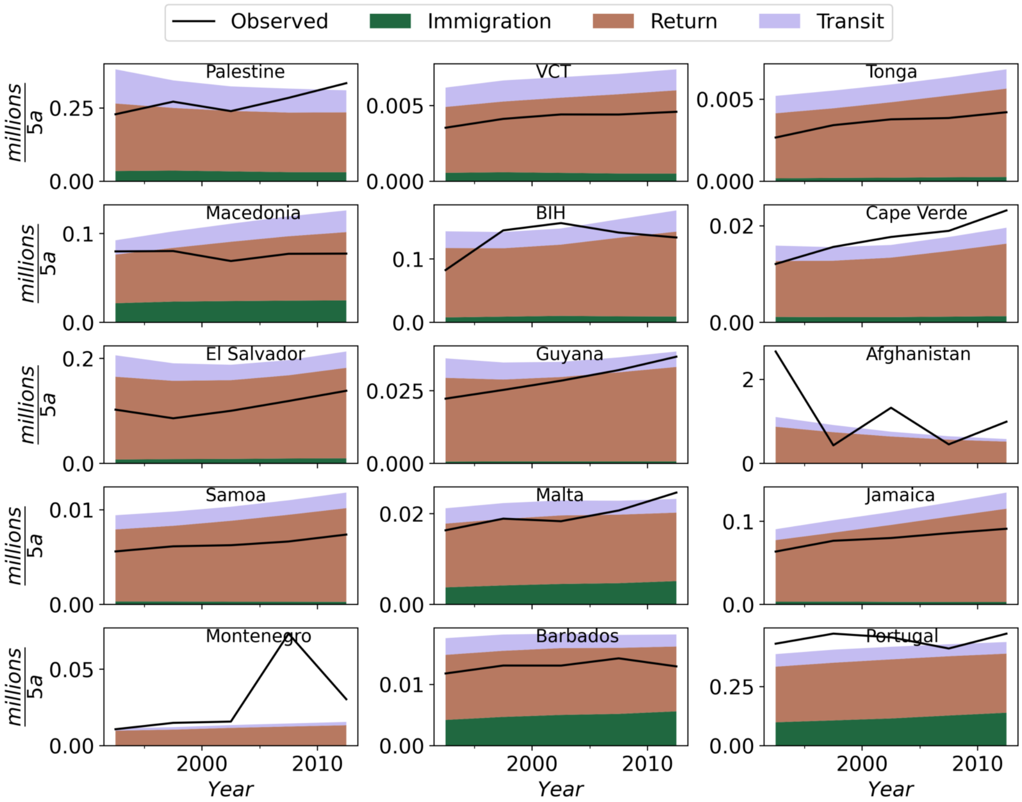


Figure 2.9: Countries and territories with substantial simulated transit migration inflows. Immigration, here, denotes inflows of natives from their respective country of birth into the reported country. Black solid line shows the observed total inflow. VCT stands for Vincent and the Grenadines, and BIH for Bosnia and Herzegovina.

net migration flows until 2040, declining from then on, and reaching, at the end of the century, lower levels of net migration compared to today. Focusing on SSP 2 and 4, results mirror the strong divergence in between-country inequality between the two scenarios, rather than average income levels. This can be seen especially in Africa.

Considering the full set of SSPs that are used for producing projections, the range of possible outcomes of migration flows is wide. When compared to other projections, produced by a linear scaling of migration flows with countries' share in global GDP [117], it appears that this range is narrower in my projections. This corroborates the hypothesis that accounting for major non-linear driving forces of migration and feedback processes is particularly relevant.

The hump shaped function, used here to relate the income levels at the origin with the emigration rates, shapes the temporal evolution of migration flows. This can be observed well when focusing on countries that undergo an economic development transition, starting from poor levels of GDPc and developing fast in cases like SSP 1 and 5, producing migration levels that converge to zero towards the end of the century. It is worth noting that in my model net zero migration emerges from the interplay between the three types of migration flows (emigration from country of birth, transit and return) and the natural population change. Therefore it emerges as a dynamic equilibrium rather than a static one, and emigration flows are generally replaced by return flows and natural population growth.

One of the major shortcomings of the model is its incapacity to capture short-term variations in migration. It rather follows a smooth dynamic evolution driven by the major forces of migration that define its long-run dynamics, neglecting short-run shocks that might be provoked by events as wars and global economic crisis. The economic models that produce the GDP projections under the SSPs do neglect these short run effects too [115]. Therefore my results may represent just a lower bound of the flows that might appear if countries followed any of the SSPs.

This simulation exercise should nonetheless be useful for studying the effect that different socio-economic trajectories would have on international migration patterns. The major innovations of my model and of the projections produced with it are represented by the non-monotonic effect of origin-country income levels, the diaspora feedback and the three type of migration flows. Nonetheless the model neglects other important factors largely influencing migration. For instance, demographic heterogeneities such as educational levels, age and sex, are important characteristics usually associated with different levels of emigration rates. To some extent these heterogeneities are already included in my model through the birth and death rates as well as the GDPc projections under the SSP scenarios. Accounting for these heterogeneities, especially separating between low-skilled and high-skilled migration, would be an important extension of the model [118]. Another possible extension would be to account for rates of assimilation of migrants into the host society. The assumptions of my model, at this initial stage, assume either infinite or null rate of assimilation. Indeed, it assumes that first-generation migrants are always part of the diaspora, never being assimilated. On the other hand children of migrants enter, by definition, the stock of natives in the country and therefore are never part of the diaspora of their parents. The reality might be in between these two extremes, with children never being assimilated or first-generation migrants that stop being part of the diaspora after some years living abroad due to losses of connection with the community at the origin. Finally, the assumptions about natural population growth through fertility and mortality rates are also simplistic but the results are robust to alternative choices (Appendix, Figures A.3 and A.18). Despite the uncertainties in both the model parameters and assumptions, they still allow for a robust separation of the future patterns and magnitude of international migration flows under the different SSPs. While the main aspect of the model's projections is to inform discussions about future global migration, they can be included into a wider framework of population models [116, 137], where migration is only one part of the demographic change.

3

Divergent effects of climate change on recent international migration patterns

Adapted from Rikani et al. "More people too poor to move: Divergent effects of climate change on global migration patterns. Environmental Research Letters, Under revision

3.1 Introduction

Observed global surface temperature shows rates of change that are unprecedented in thousands of years [81]. Climate change impacts have pervaded terrestrial, coastal, freshwater and ocean ecosystems. Moreover, their geographical coverage has reached most of the regions of the globe [138]. For its well functioning, our society is highly dependent on human-made systems such as food production and economic productivity. Climate change impacts have affected these spheres too [139, 140]. Recent studies have found robust evidence for effects of the climate and weather conditions on the economic productivity [107, 106]. When this effect assumes a parabolic relation between temperature and economic growth, it produces divergent effects of further warming depending on whether the country is warmer or cooler with respect to the optimum temperature value. Considering that warm countries are identified with the Global South, hence with poorer countries, and the opposite is valid for countries of the Global North, it follows that economic impacts of global warming may have already acted to increase the global economic inequality [110].

Economic conditions, at both origin and destination country, are recognised as important drivers of international migration [6, 37, 34]. Therefore, it appears likely that changes in these conditions, due to global warming impacts, might have produced effects on recent international migration patterns. Still, it remains unclear to which extent and through which mechanisms this effect might have acted. Here I try to fill this gap by exploring, at the global level, the role of recent climate-change-driven macroeconomic impacts on international migration, while explicating the underlying mechanisms through which economic impacts have translated into impacts on international migration.

The analysis consists in using recent innovations from three different research fields: (*i*) two approaches for estimating the impact of climate change on the economic productivity [107], (*ii*) a counterfactual without-global warming historical temperature dataset [141], (*iii*) an international migration model that accounts for the complex dependence of migration on income levels at origin and destination [142].

This complexity lies particularly on how emigration rates respond to income levels at the origin country. There is robust empirical evidence that emigration rates tend to reach a maximum for middle-income countries while they approach lower levels for both low- and high-income countries. Potential explanation for this non-linear dependence, which is usually referred as the migration hump, can be, among others, the demographic transition experienced by the country and the interplay between poverty constraint and intentions to migrate [44, 56]. This important complexity is usually not accounted for in previous models of international migration. The model developed in the first part of this thesis has the benefit of explicitly including the migration hump. I assume here that this is not just a spatial relation but it rather describes a temporal dynamics of a long-term process, termed mobility transition [143], which assumes that countries follow the migration hump function as their average incomes change. This assumption is in line with previous studies [44, 144], even though, due to a lack of time-series data, there is still not full agreement on whether it is a pure spatial relationship or a process describing a temporal evolution of the countries [45, 145].

Importantly, the migration model also accounts for the substantial role of the migrant networks at the destination country, also termed diaspora, and it can reproduce separately bilateral flows for return and transit migration. Therefore the model allows for capturing the main processes and drivers shaping international migration at a global level while remaining simple enough for a transparent interpretation of the results.

My analysis estimates the impact of global warming on international migration for a recent period, 1990-2020, referred as period of interest throughout this chapter, and is constructed as follows. First, starting from a dataset of historical country-level Gross Domestic Product per capita (GDPc), I calculate two counterfactual, without global warming, datasets of GDPc. To this end I use two different methods from the climate-economics literature that disentangle the role of climate and weather variability on GDPc from all the other factors influencing its evolution. One of them is obtained by using a panel regression analysis for calculating the global warming impact on GDPc, focusing on short-term weather variability. The other method estimates, through a cross-sectional analysis, the impact of long-term climate variation. These two methods are applied to a counterfactual dataset of temperature in absence of climate change, producing country-level counterfactual GDPc for the period of interest. This results in having three alternative time-series of GDPc, one historical (factual) and two counterfactual without global warming. Consequently, using the international migration model I calculate three alternative global bilateral migration flows matrices: a factual one obtained by using the historical GDPc and two counterfactual when using the GDPc in an hypothetical past without climate change. In order to attribute the impact of climate change on recent international migration patterns I compare the factual and counterfactual migration flows.

Recent studies have mainly focused on direct effects of climate change on migration, predominantly using temperature and precipitation as potential explanatory variables linking the two processes [86, 39, 90, 146]. Results suggest a significant effect of mainly temperature variations on international migration. However, these studies do not provide a quantification of the number of moves that could be attributed to recent climate change effects. The few studies that attempt a quantification, this is restricted to a specific global region [147], or small island states affected by sea level rise [148]. When the impact is studied through indirect effects, results identify the link between temperature and the agriculture sector as a main channel of action for climate change on international migration [105, 149].

My study complements the existing literature on different aspects: it presents a first quantification of the international moves that might have been caused by global warming impact through the specific channel of impacts on GDPc. Its geographical coverage is, at my knowledge, unprecedented including more than 180 countries globally; it investigates the effect of both short-term weather variability and long-term climate variation; it provides a clear mechanistic attribution of how climate change impacts are transmitted to migration. With regard to this last point, by accounting for non-linearities through the emigration hump function, it goes beyond estimating the potential net change in international migration moves and considers also those moves that might have been inhibited due to climate change economic impacts.

While the methods applied are associated with uncertainties, related to both the migration model and the climate change impact on GDPc, my approach is transparent and compatible with potential future works that would aim at quantifying other channels of impact.

3.2 Methods

3.2.1 Data

The source for historical (1990-2020) population data, both bilateral migrant stocks and total residents, is the data repository of the Population Division at the UN Department of Economic and Social Affairs (UN DESA) [126, 127]. Historical data of country-level GDPc, covering the same historical period on an annual level, is obtained from an extended version of the Penn World Tables (PWT) versions 8.1 and 9.0 [128, 129]. Bilateral migration flow data comes from a recently updated version of a global bilateral migration flow dataset obtained from a pseudo-Bayesian method applied to bilateral migrant stocks [103, 150]. This panel dataset provides bilateral migration flows for 202 countries and covers the period from 1990 to 2020 on five-year intervals. Due to missing data and the fact that some countries have appeared from the disaggregation[1] of other larger countries, I limit this dataset and my study to 182 countries. A list of missing countries is provided in the appendix (Appendix, section B.1). Data on refugee statistics is obtained from the UN High Commissioner for Refugees [131].

Factual temperature data covering the period 1901-2019 comes from two sources: the WFDE5 global reanalysis for the period 1979-2019 [151], and an adjusted version of GSWP3 reanalysis [152] for the period before; discontinuities at the transition period are minimized [153]. The corresponding counterfactual temperature was calculated within the framework of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP3a, [154]), by removing from the

[1] In the source dataset, Serbia and Montenegro are considered as one single country before 2010; same case for Sudan and South Sudan

factual data the long-term trend while preserving the short-term variability [141]. For some very small countries where the data was not available, the temperature of the nearest country has been used (Appendix, section B.1).

3.2.2 The migration model

I use the model developed and presented in the previous chapter as the initial point for investigating the impact of past climate change impacts on migration. The model accounts for major drivers of international migration: economic conditions at both origin and destination and socio-demographic factors as the diaspora feedback [142]. By defining the population by place of birth and residence it can capture three different types of bilateral migration flow: emigration from Country of Birth (CoB), return migration to the CoB, and transit migration of migrants to a third country different from that of birth.

These flows are calculated as described in the following equations:

$$M_{k,i\to j} = a_j \cdot F(G_i)\, g_j^{\alpha_g}\, p_{k,j}^{\alpha_p}\, P_{k,i} \qquad \text{for } k \neq j, \tag{3.1a}$$

$$M_{j,i\to j} = b_i \cdot P_{j,i}, \tag{3.1b}$$

where $M_{k,i\to j}$ represents the migration flow from the origin country i to the destination country j of people born in country k. For $k \neq j$, Equation 3.1a describes emigration from CoB and transit migration, while return migration is described by Equation 3.1b. The population stock is defined by two subscripts, the first defining the place of birth and the second defining the place of residence: $P_{k,i}$ is the population born in k and living in i. The diaspora term, $p_{k,j}$, is defined in relative terms of the total population with a certain place of birth: $p_{k,j} = \frac{P_{k,j}}{\sum_j P_{k,j}}$. The economic conditions at the origin and destination are accounted for through the GDPc values. The GDPc at the destination enters the model rescaled by the global mean GDPc: $g_j = G_j/G_{glob}$, where G_j is the GDPc at the destination country. The dependence of emigration on origin country GDPc is modelled through a non-linear function, $F(G_i)$, which is defined by the superposition of two terms:

$$F(G_i) = F_{intent}(G_i) \cdot F_{resource}(G_i) = \frac{1}{1+\frac{G_i}{\widehat{G}}} \cdot \frac{1}{1+e^{-\gamma(G_i-\tilde{G})}}, \tag{3.2}$$

with $\widehat{G}$ and $\tilde{G}$ parameters to be estimated. The first term is meant to capture the desire to migrate: it starts at a maximum for $G_i = 0$, and approaches zero for large G_i. The second term is meant to capture the dependence of the emigration rates on the economic resources: it starts at a minimum level for $G_i = 0$ and increases to a maximum level for $G_i \gg \tilde{G}$. a_j and b_i are country-specific scaling factors that would capture the effects of unobserved characteristics, i.e. quantities that would affect the migration flows but are not included explicitly in the model. For simplicity I try to keep the number of these scaling factors restricted to either origin- or destination-specific. While there would be different country-specific constant characteristics that these scaling factors would capture, I apply them with the main aim of capturing immigration policies. Indeed, immigration policies are important characteristics aiming at directly influencing migration flows and empirical results have pointed out their importance in explaining migration flows [86, 42]. There are different levels of aggregation and indexing of immigration policies [69, 37, 70]. Empirical results suggest that the regulations for entering the country are the most important component of immigration policies, compared to regulations for remaining in the country [36]. Therefore, the scaling factors a_j and b_i are used with the objective of capturing entering regulations. I assume that regulations at the destination apply to people moving from their CoB or moving to a third country, hence a_j is a destination country-specific factor. On the other hand, I assume that regulations for entering the country do not apply to natives returning to their country of birth (i.e. return migration). Nonetheless, return flows might be influenced by restrictions applied at the origin country: empirical results suggest that restrictions for entering the country would reduce also the outmigration from the country [75]. In order to capture this effect I use origin country-specific factors, b_i, in the equation describing return migration.

In its original version the model accounts also for natural population change due to births and deaths, and the population stocks are updated iteratively in each step by the net migration flows and natural change. Since the temporal dynamics captured by the original model reflects rather long-term processes and the model can not capture short temporal variations of the bilateral migration flows [155], I apply it here in its static version, i.e. without dynamically updating the population stocks at each step. After estimating the parameters of the model I evaluate Equations 3.1a and 3.1b at the beginning of each five-year interval within the historical period of interest 1990-2020, using the historical GDPc and population. I calculate the same bilateral flows using the two counterfactual time series of GDPc. Thus, for each interval I produce three matrices of bilateral migration flows, one factual and two counterfactual.

3.2.3 Global warming impacts on GDPc

The global warming impact on the economic productivity is captured by using two different methods, both coming from a recent empirical study which investigated the impact of global warming at different temporal scales on sub-national levels of GDPc (K20, [107]). The first method that I use comes from the results of the cross-sectional analysis, equation 8 in K20. The analysis uses averaged (decades) values of temperature and precipitation as explanatory variables, along with regional specific geographical and endowment resources characteristics, while controlling for country-specific unobserved variables through fixed effects. Since precipitation variables are not statistically significant in the analysis, I neglect them in my specification and the log-linear damage function, in my case for the national GDPc, reads as follows:

$$\ln G_{t,i} = \alpha_T \tau_{t,i} + \ln \tilde{G}_{t,i}. \tag{3.3}$$

As assumed in K20, α_T, is negative and the term in Equation 3.3 that includes it, represents the impact of long periods averaged temperature levels: $\tau_{t,i} = \frac{1}{5}\sum_{l=0}^{4} T_{t-l,i}$, where $T_{t-l,i}$ are annual values of temperature. The second term, $\ln \tilde{G}_{t,i}$, represents the temperature-independent term of the GDPc of the country. Therefore, following Equation 3.3, the factual and counterfactual temperatures will produce different effects on the GDPc;

$$\begin{aligned} \ln \mathrm{G}^{\mathrm{obs}}_{t,i} &= \alpha_T \tau^{obs}_{t,i} + \ln \tilde{\mathrm{G}}_{t,i}, \\ \ln \mathrm{G}^{cf}_{t,i} &= \alpha_T \tau^{cf}_{t,i} + \ln \tilde{\mathrm{G}}_{t,i}, \end{aligned} \tag{3.4}$$

where the superscript *cf* represents the counterfactual case and *obs* the factual. The counterfactual GDPc is obtained by solving the system of Equations 3.4 for $\ln G^{cf}_{t,i}$:

$$\ln G^{cf}_{t,i} = \ln G^{obs}_{t,i} - \alpha_T \tau^{obs}_{t,i} + \alpha_T \tau^{cf}_{t,i}. \tag{3.5}$$

Solving this last equation for $G^{cf}_{t,i}$ yields a relation for calculating the counterfactual GDPc from the factual one:

$$G^{cf}_{t,i} = G^{obs}_{t,i} \cdot e^{-\alpha_T \Delta\tau_{t,i}}, \tag{3.6}$$

where $\Delta\tau_{t,i} = \tau^{obs}_{t,i} - \tau^{cf}_{t,i}$.

The second method for estimating the global warming effect on the economic productivity follows the results from the panel regression analysis in K20. From equation S7 in K20, Supplementary material, the GDPc growth rate can be disentangled in two terms:

$$g_{t,i} = \delta(T_{t,i}) + \tilde{g}_{t,i}, \tag{3.7}$$

where $\delta(T_{t,i})$ represents a loss term that depends on annual temperatures levels and changes, and $\tilde{g}_{t,i}$ is the unperturbed term in country i and time t. The loss term consists in:

$$\begin{aligned} \delta(T_{t,i}) =& \alpha_1 \Delta T_{t,i} + \alpha_2 \Delta T_{t-1,i} + \\ & (\beta_1 \Delta T_{t,i} + \beta_2 \Delta T_{t-1,i}) \cdot \\ & \left(T_{0,i} + \sum_{s=1}^{t-1} \Delta T_{s,i} \right) \end{aligned}, \tag{3.8}$$

where α_1, α_2, β_1, and β_2 are constant factors and $\Delta T_{t,i} = T_{t,i} - T_{t-1,i}$ represents annual changes in temperature. $T_{0,i}$ in my study is the temperature in 1901, and $\Delta T_{0,i}$ is assumed to be zero. As for the first method I can specify Equation 3.7 for both the factual and counterfactual case:

$$\begin{aligned} g^{obs}_{t,i} &= \delta(T^{obs}_{t,i}) + \tilde{g}_{t,i} \\ g^{cf}_{t,i} &= \delta(T^{cf}_{t,i}) + \tilde{g}_{t,i}. \end{aligned} \tag{3.9}$$

I solve the system of Equations 3.9 for the counterfactual growth rate, $g^{cf}_{t,i}$, and using the relation linking the growth rate to the GDPc level, $g_{t,i} = \ln G_{t,i} - \ln G_{t-1,i}$, I can express the counterfactual GDPc in terms of the difference in warming between factual and counterfactual cases:

$$G^{cf}_t = G^{cf}_{t-1} \cdot e^{g^{obs}_t - \Delta\delta_t}, \tag{3.10}$$

where I have omitted the country subscript in the notation and introduced $\Delta\delta_t = \delta(T_t^{obs}) - \delta(T_t^{cf})$. Equation 3.10 is recursive and by iterating it backwards I can express the GDPc at time t by its initial value at time t_0:

$$G_t^{cf} = G_{t_0}^{cf} \cdot e^{\sum_{t'=t_0+1}^{t} g_{t'}^{obs}} \cdot e^{\sum_{t'=t_0+1}^{t} -\Delta\delta_{t'}}. \tag{3.11}$$

If the initial year is assumed without global warming impacts then, by definition $G_{t_0}^{cf} = G_{t_0}^{obs}$, and the counterfactual GDPc can be related to the factual one and the difference in the temperature-dependent growth rate:

$$G_t^{cf} = G_t^{obs} \cdot e^{\sum_{t'=t_0+1}^{t} -\Delta\delta_{t'}}. \tag{3.12}$$

The values used for the parameters of both methods are reported in Table 3.1.

Table 3.1: Parameters used for the methods of global warming impact on economic productivity, taken from K20.

Variable	*Parameter*	*Value used*
Cross-sectional	α_T	-0.023
Panel	α_1	0.00641
	α_2	0.00345
	β_1	-0.00109
	β_2	-0.000718

3.2.4 Parameters estimation

The approach for estimating the parameters of the migration model in Equations 3.1a, 3.1b and 3.2 follows closely the methods used in the first chapter and reported in the first paper [142]. The method consists in three steps regression. First, I estimate the parameters $\widehat{G}$, γ and $\tilde{G}$ in the function $F(G)$. Since the function $F(G)$ is not meant to hold for refugee flows, and these are included in the original bilateral migration flow dataset, I attempt to exclude bilateral refugee flows from the original dataset. I follow the methods in ref. [142] and calculate bilateral refugee flows from a simple reverse demographic method for obtaining flows from stocks (see Subsection 2.2.3). The emigration-GDPc function is also not applied to return flows (see Equation 3.1b), therefore I exclude return flows too from the observed data. Since I can not access and exclude explicitly these flows because the released data is aggregated to origin-destination flows, I assume that return flows are mainly defined by the condition of origin GDPc being larger than twice the GDPc at the destination (see Subsection 2.2.3). After excluding return and refugee flows from the original dataset I aggregate the data for obtaining total emigration flows for each country. I fit the migration hump function to country-level emigration rates, i.e. after dividing the total emigration by the total population in the origin. In the next step I focus on the remaining global parameters of the migration model. To this end I disentangle the country-specific scaling factors into two terms, one remaining country-specific and the other being global and referring to the migration type: $a_j = a \cdot \tilde{a}_j$ and $b_i = b \cdot \tilde{b}_i$.

Due to the high collinearity of these factors I decide to estimate first the global parameters of the migration model. Following the methods in ref. [142], I use a non-linear regression method where the original observed bilateral flow, $\hat{M}_{i\to j}$, is regressed against the sum of the emigration from CoB and return migration:

$$\hat{M}_{i\to l} \approx M_{i,i\to j} + M_{j,i\to j} \approx a \cdot \tilde{a}_j \cdot F(G_i) \cdot g_j^{\alpha_g}\, p_{i,j}^{\alpha_p}\, P_{i,i} + b \cdot \tilde{b}_i \cdot\, P_{j,i}, \tag{3.13}$$

where the function $F(G_i)$ is evaluated using the parameters obtained in the first step, and the country specific scaling factors have been set to 1. In the last step I estimate, through a linear regression on the averaged bilateral flows of the historical period, the country-specific scaling factors (Equation 3.13):

$$\hat{M}_{i\to l} \approx \sum_{k\neq j} M_{k,i\to j} + M_{j,i\to j} = a \cdot \tilde{a}_j \cdot \sum_{k\neq j} F(G_i) \cdot g_j^{\alpha_g}\, p_{k,j}^{\alpha_p}\, P_{k,i} + b \cdot \tilde{b}_i \cdot\, P_{j,i}, \tag{3.14}$$

where for the global parameters I use the values estimated in the first and second step. The estimated values of the global parameters are reported in Table 3.2, while the values of the country-specific factors are reported in the Appendix, Table B.1.

My estimation is associated with uncertainties in the parameters, with the major source being the parameters defining the migration hump function. I include a sensitivity analysis by using my model with the migration hump function evaluated for different values of its parameters. Besides the central estimated values I use the lower and upper extremes associated with their confidence interval. I change the value of one parameter per time while keeping the others at their central value. Using these different parameters sets I calculate, as described above, factual and counterfactual matrices of migration flows. The difference between factual and counterfactual flows, for each of these sensitivity cases, constitutes a measure of uncertainty in the model's response and is shown in the representation of the results.

3.3 Results

3.3.1 Estimation results

The first step of the estimation, where the parameters of the function $F(G)$ are estimated using the total relative emigration flows, gives results in line with previous studies, showing a peak of migration rates at values of ~ 3500 \$ [142]. The fit also matches well a non-parametric regression to the same data (Appendix, Figure B.1). The second step of the estimation, which produces estimates for the global parameters of the migration model, gives results in line with previous works. That is, destination GDPc has a positive effect on immigration and the diaspora represents a strong factor for attracting migrants. The estimates are reported, with respective confidence level in Table 3.2.

The estimated values of the country-specific scaling factors are shown in the Appendix, Figure B.2 and Table B.1.

Table 3.2: Parameters used for the international migration model and the climate change impact methods. Parameters regarding the migration model are reported with the respective confidence level. Parameters for the migration hump reported with 66% confidence level. The remaining global parameters are estimated from the bilateral migration data and reported with a confidence level of 99%.

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 ± 9356
	$\widetilde{G}$	\$ 929 ± 139
Return migration		
Intercept	b	0.124 ± 0.001
	R^2	0.69

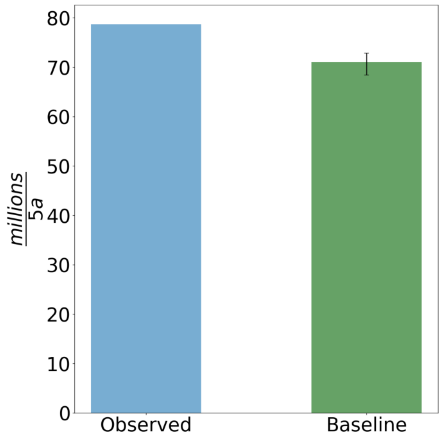
3.3.2 Global warming impact on recent international migration patterns.

I produce a matrix of global bilateral migration flows for each five-year interval within the recent period, 1990-2020, for the factual and counterfactual cases. Results are aggregated along the temporal dimension, obtaining one representative matrix of bilateral flows for the entire period, separately for the factual and each counterfactual case. The two counterfactual cases correspond to hypothetical pasts without global warming. Each of them is obtained by using one method of global warming impact on economic productivity. One, termed *short-term* case, is based on a panel regression analysis and reflects the impact of weather shocks happening on short time scales and does not account for adaptation strategies. The second case, termed *long-term*, results from a cross-sectional analysis, and considers impacts due to the climate variations happening on longer temporal scales.

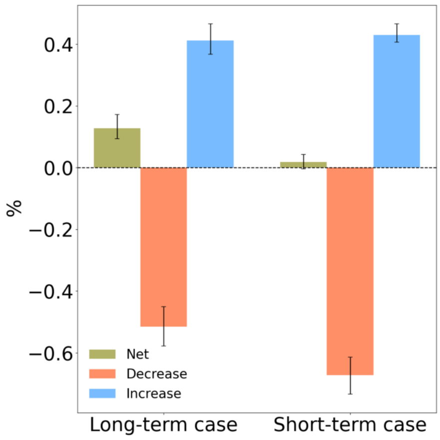
In order to produce reliable attribution results of climate change impact on migration I show first the performance of the model in reproducing observed flows. Therefore, I compare the flows reproduced by the model under the factual case to those observed [150].

At the global level the model estimates, on average per five-year interval, about 70 million migration movements (Figure 3.1a). This is slightly smaller than the size obtained from the observed data and a possible explanation can be the refugee flows, which the model is not meant to capture and can not capture but are included in the observed flows.

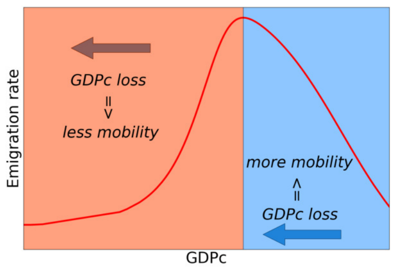
At the country level the model captures well the magnitude of averaged immigration and emigration flows for many countries (Figures 3.2a-d). For few small countries the differences in emigration can be very large, exceeding values of 100%, e.g Kiribati. Besides these few and small countries, for the majority of them the difference for emigration flows, in relative terms of observed flows, stays in a range of ±20%, with peaks of ±60% (Figure 3.2e). It is worth noting that these extremes would have been more frequent if I had not used country-specific scaling factors (Appendix, Figure B.3a). The regions where the model shows the largest differences compared to the observed data are Africa and Southeast Asia, as well as some countries



(a)



(b)



(c)

Figure 3.1: Averaged global migration flow for the historical period 1990-2020 and representation of the mobility transition used in the model. Panel (a) shows a comparison of global averaged migration flow, between the observed data and the model output under the factual case. Panel (b) reports the difference between the factual and each of the two counterfactual cases, in relative terms of the counterfactual results. Positive values represent larger migration under the factual case. The difference is shown separately for the net change in global mean flow as well as for the averaged total increase and decrease. Black lines show the extremes reached within the sensitivity analysis where, one per time, the lower and upper values of the migration hump function parameters are used to produce migration flows (see Methods). Panel (c) shows an illustration of the diverging effect produced by GDPc loss on emigration rates. The red curve represents the estimated migration hump function (Appendix, Figure B.1).

in East Europe and Middle East. These are regions largely affected by refugee flows [131], corroborating the hypothesis that a main limit of the model in reproducing observed flows is its incapacity of capturing refugee flows. Immigration flows are well captured for many large countries and show predominantly an underestimation pattern, apart from some countries in South Asia, Africa, South and Central America (Figure 3.2f and Appendix, Figure B.3b).

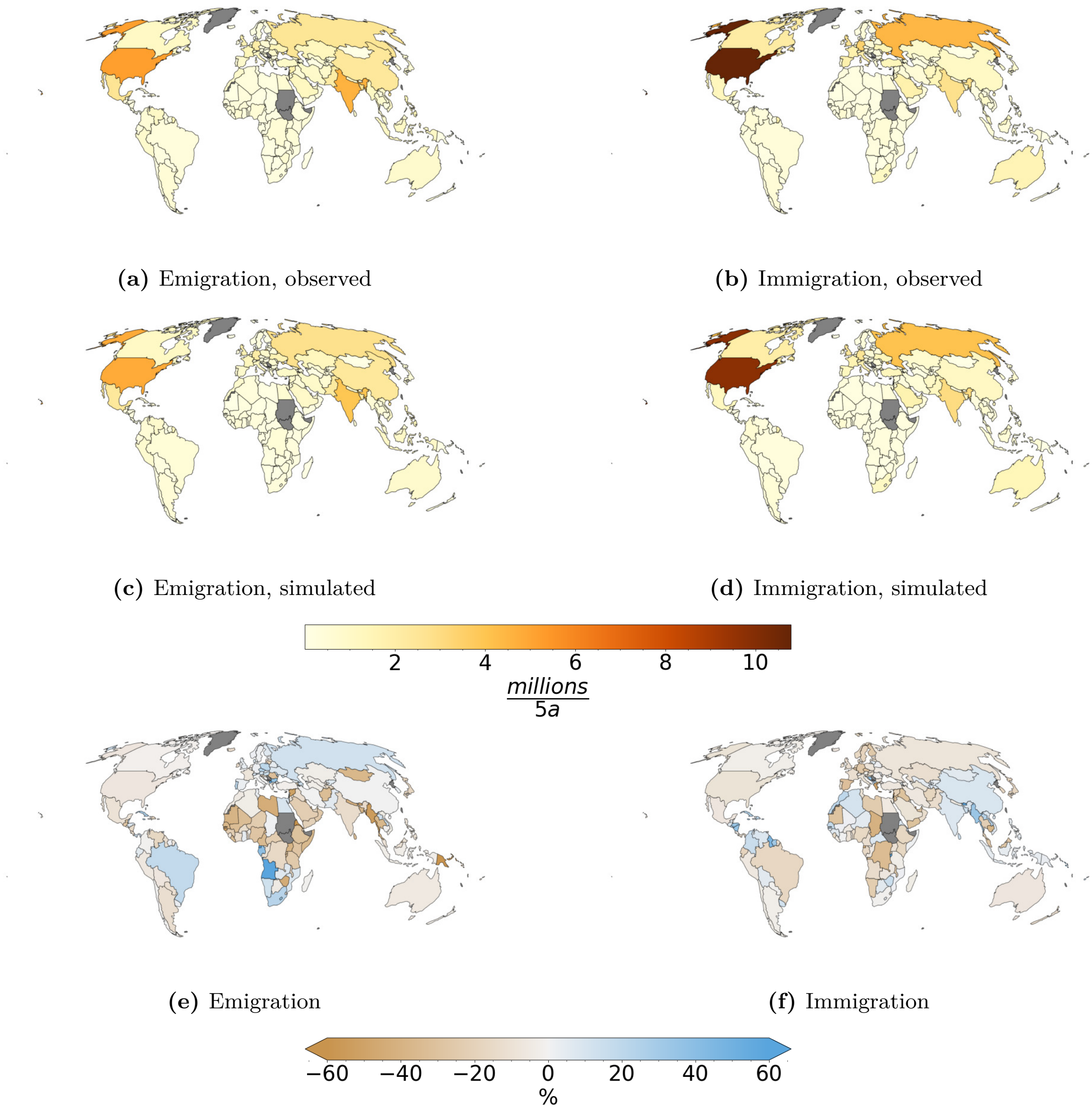


Figure 3.2: Country level, averaged migration flow levels for the period 1990-2020, for observed and model output under the factual case. Panels (a,b,c,d) show the migration level. Panels (e) and (f) show the difference between simulated and observed migration, in relative terms of observed flows. Positive values represent larger simulated than observed flows.

I turn now to the results regarding the counterfactual scenarios where two different methods of global warming impact on the GDPc have been used. Under the long-term case the impacts, on average for the period of interest, are relatively homogeneously distributed and are predominantly negative, representing losses in GDPc[2] (Figure 3.3a). On the other hand, under the short-term case the impacts show a divergent spatial pattern, with countries in north

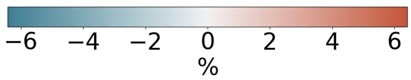
[2]This means that in the counterfactual case countries would have experienced higher levels of GDPc during the historical period.

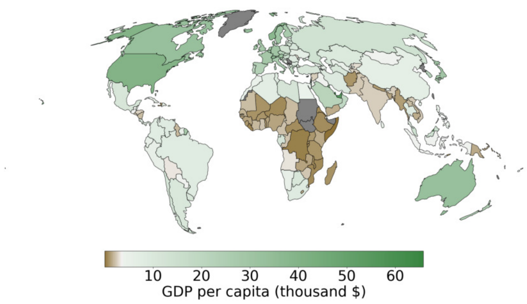
latitudes presenting small losses or even gains in terms of GDPc, while countries in souther latitudes show predominantly losses, which in many cases are larger than those experienced under the long-term case (Figure 3.3b). These results are in line with previous works about past and future global warming impacts on economic conditions of the countries [110, 107].

These economic losses affect migration flows in the model through the function describing the emigration rates dependence on the GDPc (Equation 3.2), and through the term of destination country relative GDPc. Specifically, considering the effect on the migration rates function, a loss in GDPc of the country translates, in terms of emigration rates, into a decrease or increase, depending on whether the factual level of GDPc is respectively at the left- or right-hand of the peak of the migration hump function (Figure 3.1c and Appendix, Figure B.1).

(a) GDPc difference, long-term

(b) GDPc difference, short-term case





(c) GDPc level, historical

Figure 3.3: Country level, global warming impact on GDPc under the long-term (a) and short-term (b) cases. The represented impact is calculated as the relative difference of the factual GDPc and the counterfactual case, relative to the counterfactual case. Positive values show cases where the factual GDPc is larger than the respective counterfactual, i.e. gains that countries might have experienced due to the impact. Panel (c) shows the absolute level of the factual GDPc. The white center of the diverging color scale corresponds to the peak of the estimated migration hump function (Appendix, Figure B.1). All figures represent averaged levels for the historical period of interest.

These global warming impacts on GDPc lead to the following results in terms of international migration. Through the effect on the economic development of the country, global warming may have resulted in a net difference of migration moves, globally and per five-year period on average, of $\sim 0.15\%$ and $\sim 0.05\%$ under the long- and short-term method respectively. However, these figures do not give a comprehensive insight on the effective impact because some bilateral flows may have decreased and others may have increased due to the same impact.

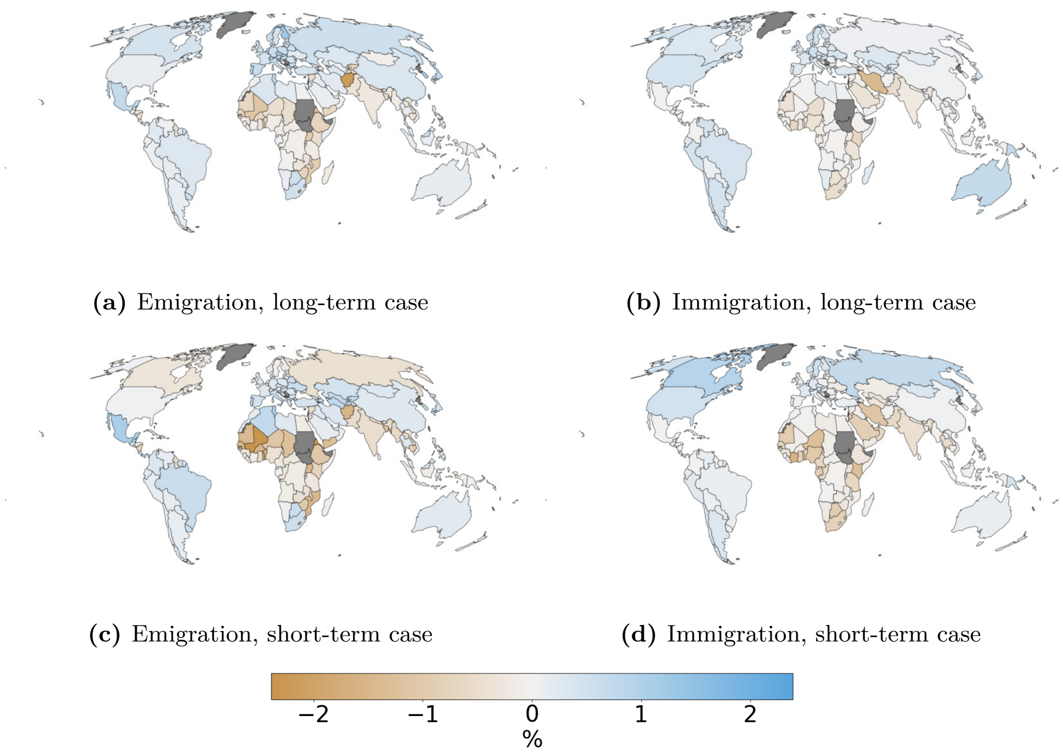
Therefore, I reproduce figures of global increase and decrease, separately, constructed from the bilateral flows. That is, I consider separately the bilateral flows that would have increased and decreased and calculate the difference relative to this subset of flows rather than to the global one. These values are substantially larger than the net figures, amounting to roughly $0.5\% - 0.7\%$ decrease and to $0.4\% - 0.5\%$ increase (Figure 3.1b). Results are similar between the two methods of impact with slightly larger decrease observed under the short-term case.

Overall these results indicate that the net change of migration might not give a satisfactory information on the real magnitude of impact of climate change. More meaningful can be the numbers of totally affected moves, which are obtained as the sum of the absolute values of increase and decrease. This can be interpreted as the percentage of the total number of moves that were potentially affected by the impact, either being inhibited or induced. Reaching a value of $\sim 1\%$, this number suggests that global warming might have been a small but significant contributor to past international migration patterns.

At a higher resolution of the country level, the two methods of global warming impact produce similar spatial patterns of reaction in migration. Patterns are also similar between emigration and immigration, showing a decrease in Sub-Saharan and South Asian regions and small differences or increase in the other regions (Figure 3.4).

These regional patterns show different heterogeneities when considering countries individually. For instance, countries in the northern latitudes show an increased emigration due to climate under the long-term case, while the impact results in having reduced migration flows under the short-term impact method. These results are largely explainable by the effect of global warming in these countries under the two methods of impact and the mobility transition assumed by the model (Figures 3.1c, 3.3a and 3.3b). That is, countries in northern latitudes, which have already crossed the peak of the migration hump (Figure 3.3c), will move towards lower levels of emigration if they experience gains in terms of GDPc and to higher levels of emigration if they experience losses. This is the case of Canada and Russia, for example, where the short-term impact finds that global warming has increased GDPc while it has reduced it under the long-term method. Divergent effects are found also between immigration and emigration, in these and some other countries in West and Central Asia. A potential explanation might be that for these countries the source of immigration are mainly countries that have seen a decrease in emigration.

Considering that regional patterns emerge from the country-level figure of differences in emigration and immigration due to climate change (Figure 3.4), I analyse also the results at the aggregated level of bilateral regional flows (Figure 3.5). Results mirror what has been observed for the country and global level, with the two methods of impact leading to similar induced differences in migration and the magnitude of the effect being larger under the short-term method. Under both counterfactual cases I find that climate change has reduced internal migration in Africa, South and West Asia, while it has increased internal migration in Europe and Former Soviet Union. Migration from Europe and East Asia to North America is estimated to have increased substantially due to global warming impacts. Driven mainly by the flow from Mexico, migration from Latin America to North America shows equally a substantial increase due to global warming impacts. Remarkably, I find very small effects on common



(a) Emigration, long-term case

(b) Immigration, long-term case

(c) Emigration, short-term case

(d) Immigration, short-term case

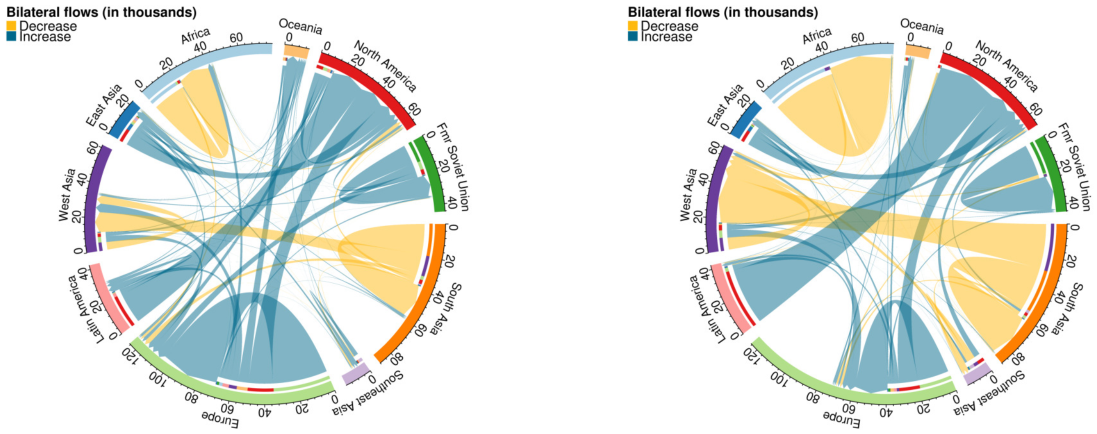
Figure 3.4: Country level, relative difference of immigration and emigration due to climate change impacts under long-term (a,b) and short-term (c,d) methods. Positive values represent larger flows under the factual case relative to each counterfactual case. All figures represent averaged values of the historical period of interest 1990-2020.

migration routes from the Global South to the Global North such as, Africa to Europe, South and Southeast Asia to either Europe, North America and Oceania.

This last result appears, at a first glance, counter-intuitive since these routes of migration are often key topics of concern and discussion in countries of Global North, also in terms of policies regarding how these flows would react to climate change [156].

However, my mechanistic and explicit approach of modelling migration and the explication of the channel through which the global warming impact transfers to migration, can give a transparent understanding of these patterns. The global warming impact on the GDPc enters in my model through two terms: the emigration hump function, which describes how emigration rates depend on GDPc at the origin, and the relative GDPc at the destination country. The migration hump used here has a peak around a value of $\sim 3,500\$$ GDPc. Consider, for instance, a country that is estimated to have had a negative economic impact from climate change, i.e. it has a factual GDPc lower than it would have had without the impact. This is the case for almost all countries in the long-term case[3] (Figure 3.3a). Within this set of countries, consider a country that is relatively rich in the factual case, i.e. that lies on the right-hand of the peak of the estimated migration hump (Figure 3.1c; green in Figure 3.3c). This country would have had larger values of GDPc without the impact and therefore would have been situated further on the right side of the emigration-GDPc relation expressed by the migration hump. This higher level of GDPc would have been associated

[3]The only countries experiencing a positive effect in this case are Cape Verde and Bolivia. For the latter, the small positive effect is likely due to the fact that climate data shows a pattern of cooling for this region of Latin America (Figure 5 of ref. [141])



(a) Long-term case

(b) Short-term case

Figure 3.5: Impact of global warming on averaged bilateral migration flows between ten major world regions under the long-term (a) and short-term (b) case. Increases represent cases where the impact would produce larger migration flows under the factual case than under the counterfactual without climate change scenario. The external thicker arc defines the region of origin, and arrows depart from the origin and point to the destination region. For better visualization the destination region is represented in the thinner, internal arcs. For instance, global warming under the short-term case, is estimated to have decreased migration from South Asia to West Asia by about 30,000 per five-year period (thick yellow arrow across the center of panel (b)). Countries included in each region are listed in the Appendix, Table B.1.

with lower levels of emigration rate (Figure 3.1c). For this same reason, if the country is relatively poor, i.e. its GDPc is lower than the peak of the migration hump (Figure 3.1c; brown in Figure 3.3c), migration flows in the counterfactual case would have been higher than in the factual case. This process is followed in the opposite direction in cases where the country is estimated to have gained from the global warming impact, as it happens for some countries in northern latitudes (Figure 3.3b). The country would have had a lower GDPc in the counterfactual case without global warming, which would have taken it to values of GDPc associated with higher (lower) emigration rates if it is a relatively rich (poor) country, in terms of the migration hump.

The second channel for global warming impacts to affect migration in the model's specification, is the relative destination country GDPc. While the relationship between this factor and migration is monotonic, i.e. larger is this term larger will be the attracted migration flow (all else being equal), the fact that it is expressed in terms of global mean GDPc makes it sensitive to the type of impact method that is considered. Consider for example a country that experiences the same loss due to climate change impact, under both short- and long-term methods. The impact in terms of global mean GDPc will likely be smaller under the short-term method compared to the long-term method because the losses experienced by some countries may be replaced by the gains in other countries, under the short-term case. On the other hand, under the long-term method almost all countries see a negative impact and therefore these economic losses can not be replaced by gains of other countries. This means that the same impact on the GDPc of a country would produce a smaller relative GDPc under the short-term method, because the global mean GDPc would be higher. This effect would translate, in the model, in countries attracting less migrants under the short-term method than under the long-term [4].

Results remain complex to interpret because of the dependence of each bilateral flow on the GDPc in all the other countries, and migration flows are aggregated along different dimensions. Nonetheless, the processes described above give a substantial explanation of the observed spatial patterns. Climate change impact, by reducing the GDPc of poorer countries has pushed them further away from the peak of the function describing the relation between GDPc and emigration rates, therefore reducing emigration from these countries (Figures 3.4a and 3.4c). Since these countries have large emigration flows into countries within the same region, I find a decrease of the regional internal flow for Africa, South and West Asia (Figure 3.5). Negative impacts have affected also many richer countries, but conversely this negative impact has pushed them closer to the peak of the emigration-GDPc function, resulting in increased emigration flows. Therefore I find an increase in migration flows from and between richer regions. Under the short-term method these divergent patterns of reaction are reinforced by the fact that different countries at higher latitudes, already being part of the Global North, are found to have had a positive impact from climate change (Figure 3.3b). As described above, this might have led them to be relatively more attractive destinations for migrants. On the other hand, poorer countries might have seen reduced even more their relative power of attracting migrants, which originate mainly from the same poor regions, leading to an overall reduction of mobility within the region.

3.4 Discussion

This study has produced an estimation of the impact that climate change might have had on international migration flows, globally, during the recent period of three decades. The overall pattern that emerges is that climate change, acting through impacts on the economic productivity of the countries, has resulted in increasing mobility in the richer regions of the world and decreasing it in the poorer regions, compared to a counterfactual world in absence of global warming. This is in particular the case of flows from Africa to North America or Europe. Nonetheless, income differences in middle- and high-income regions are important factors that under climate change impacts drive migration out of regions like Latin America into rich regions like North America. More economically heterogeneous regions as West Asia, which includes high-income countries as Israel and the Gulf states, low income countries as Yemen and countries like Turkey with strong migration ties with Europe, show both increases and decreases of bilateral flows to other regions.

These results are driven by the underlying specification of my migration model, that is the covariates included to explain migration flows and the functional form with which they enter the model. Existing bilateral migrant stocks, termed diasporas, are a major driver shaping international migration flows [35, 34]. Therefore, changes happening in a country will produce major effects in the bilateral flows with other countries that already share strong ties. Absolute

[4]The net result here might appear less straightforward because the impacts under the short-term method produce larger losses in GDPc and therefore even if some countries gain in terms of GDPc, these gains might not be sufficient to cover the losses experienced by the others and might turn to larger net global losses than under the long-term case.

levels of income determine emigration rates from the country in a non-linear way, with the highest rates associated to middle-income countries [44]. Between country relative income differences influence the redistribution of the total emigration flow within the set of destination countries [55].

While these relations are supported by plausible theory, they have mainly been demonstrated in cross-sectional or panel regressions, but less in time-series analysis. This means that they hold robustly for explaining spatial patterns of migration but less for explaining the temporal dynamics. Indeed, recent results indicate that commonly used gravity models for describing international migration do not capture the temporal variations of bilateral migration flows [155].

Therefore, the assumption defining my results is that the processes I have included reflect mechanisms that hold in different time periods and different climate conditions, and their effect on short periods is masked by other processes. This applies specifically to the migration transition assumed in my model, where countries follow the prescribed inverse U-shaped curve describing an emigration life cycle as their GDPc changes [45]. This means that my results should be interpreted as estimates produced by the long-run dynamics of drivers and mechanisms thought to shape international migration patterns.

The model is also limited in the number of variables for which it accounts explicitly and for heterogeneities within countries. While the estimated emigration-GDPc relation produces a smooth variation of emigration rates as income levels change, and therefore reflects the fact that for each GDPc there might by still a portion of the population too poor to migrate, it does not account explicitly for differences in within-country income distributions, nor for changes of these distributions that might have happened in the past, also due to climate change [157, 158, 159]. Including these factors in the model represents an important step for refining the study. The model also attempts, in a crude approach, to capture dependencies of international migration flows on immigration policies. In the absence of a global dataset of immigration policy index, in this study I tried to capture this dependency by using country-specific scaling factors. It needs to be recognised though that country-specific scaling factors, by definition, can not be associated explicitly to a specific variable because they would capture all the factors that are country-specific and constant. Since immigration policies are important factors shaping global migration [36, 37], accounting explicitly for these factors would also represent an important future development of the migration model. Refugee flows represent a large component of the total migration flows in some specific regions [131]. The model does not include an explicit representation for these flows. Nonetheless the model distinguishes between return and transit flows as well as emigration from country of birth, a level of heterogeneity that is not commonly included in previous works.

With regard to the counterfactual scenarios that I used, they assume that both the population distribution and the migration hump function are not affected by the recent climate change. Given the uncertainty related to the exact location of the peak of the migration hump [160], and that climate change impacts have already affected the global economic growth [110], it appears possible that in counterfactual scenarios the peak of the migration hump may have been located at higher values of GDPc. This would also be in line with the theory that is relative deprivation rather than absolute poverty that defines emigration [55]. However, while a shift in the emigration hump function would affect the exact number of migration moves, it would not produce substantial changes in my qualitative results as long as mobility increases with the rise of income levels in low-income countries and decreases with the rise of income levels in middle- and high-income countries. In more general terms, since both the population distribution and the GDPc are exogenous terms in this version of the model, my results neglect dynamic adjustments of these variables that would have occurred during the past as factual and counterfactual temperatures diverged. In other words, migration flows as well as GDPc would have reacted to different conditions, leading to, potentially, different migration flows and therefore different migrant stocks.

Moving to the climate change impact methods employed in my study, they substantiate previous studies [e.g. 106, 161] under two main aspects. First, the cross-sectional analysis allows to account for long-term economic responses, including adaptation, to slow changes in climate. Second, the analysis uses data on economic productivity at a subnational level. This is a major benefit when running cross-sectional analysis since the subnational level data allows for using country-specific fixed effects. While there is robust empirical evidence that climate change, measured through the temperature variability, produces macroeconomic impacts [162, 163, 164, 165, 108], it remains unresolved to which extent societies and economies adapt to these impacts. Employing two different methods for estimating the global warming impact on the GDPc gives a range of possible outcomes, that are transparently linked to one specific channel of impact (macroeconomic) via one specific climate variable (temperature). Still, temperature variability is not the only climatic variable associated with climate change macroeconomic impacts. On this regard changes in precipitation has shown an important effect on economic productivity [109].

Given these limitations, this study should be interpreted as a first step in quantifying the indirect effect of recent climate change on migration. It is, to my knowledge, the first attempt to quantify the attribution of climate change on recent human international migration patterns, globally and focusing on the specific indirect effect of macroeconomic impacts, while being simple enough to explicate the mechanisms driving it. Further research is needed to refine the methods proposed here for modelling international migration and including other channels of climate change impacts as well as other climate variables that might capture climate change impacts on the society and on international migration.

4

International migration under future climate change: exploring the effect of the macroeconomic channel

4.1 Introduction

The impact of future global warming is projected to hit both natural and human-made systems, affecting the well functioning of our societies by impacting the food security and economic growth, among others [10]. International migration flows may respond to these impacts too [11]. Therefore, estimating the magnitude and direction of this response might be of relevant importance for preparing future societies. These estimates would also provide evidence for understanding whether the response will act in the direction of increasing or lowering other climate-related risks such as population's vulnerability or exposure.

However, estimating this response can be complicated because of the complex pathways through which climate change might act on migration. While this causality link can become much more simple and direct in specific cases, like people fleeing in response to storms and floods [166], it remains otherwise complex [8]. This can be especially true for international migration, where the decision to migrate emerges from a multitude of factors, also non-environmental [167, 168, 34].

This difficulty has led to only few studies that have tried to produce projections of international migration due to climate change. These projections, usually based on extrapolation of past statistical relationship between climate variables and migration, are mainly limited to specific countries or regions and to aggregated (net or total emigration) flows (see [88] and ref. therein). Therefore, there is a research gap in producing projections of international migration driven by climate change and where the mechanisms that connect this two phenomena are explicated.

In this third part of my research I aim at contributing to reduce this gap by investigating one specific pathway: the effect of climate change on international migration projections using the indirect channel of climate change impacts on economic development. Economic conditions at the origin and destination country, usually measured in terms of Gross Domestic Product per capita (GDPc), are fundamental factors driving international migration [6, 42, 37]. Robust empirical evidence suggests that these same economic factors will experience a significant impact from climate change and this impact might not be homogeneously distributed across the globe [106, 107]. Hence, the question that I try to answer is: how such economic impacts will affect, globally, international migration patterns?

In order to answer to this question, assumptions have to be made about how the future levels of income, at both origin and destination, will affect migration. Due to the limited temporal dimension of migration flow data and the high level of short-term variability that they show, constraining these assumptions to past migration data is not easy. Indeed, has been shown that commonly used gravity models of international migration are not able to capture the temporal variation of bilateral international migration flows [155]. Nonetheless, there are spatial patterns that clearly emerge from migration data and I assume that they hold valid in the future period of interest that I consider in this study. Robust empirical findings suggest that the destination country GDPc has a positive effect on immigration: richer is the country, more migrants it attracts [42, 37]. I assume that this effect holds in the future in relative terms of global mean GDPc. This allows for keeping a definition of comparative terms, such as richer and poorer, relative to the future economic global status. This also means that countries are more or less attractive for receiving migrants compared to other destinations and not in absolute terms.

Assumptions regarding the origin country GDPc and emigration can be more difficult since the relation between the two terms is more complex and still under discussion. On one hand, many studies have found the presence of a non-monotonous dependence of country-level total emigration rates on average income levels [44, 142, 45]. This inverted U-shaped relation, commonly named migration hump, can be explained as the result of the combination of aspiration and capability to migrate [56, 51, 26]. Aspirations, starting from high levels in very low income countries, would decrease as incomes rise[1]. The capability, usually referred to the possibility to afford the economic costs of international migration, starting from very low levels in poor countries, increases with the rise in incomes. The superposition of these two processes would lead to observing the highest rates of emigration from middle-income countries, where the migrants could afford the costs of migrating and would still expect a substantial gain in terms of income. Other factors, like the demographic transition, have been suggested for explaining the observed migration hump pattern [44]. However, it is uncertain whether the migration hump emerges as a purely spatial pattern or it actually defines a dynamic process (migration transition). In other words, it is not totally clear whether countries track the migration hump as the level of incomes evolves. Available migration data has led to contrasting results [46, 45]. One possible explanation to the divergent results can be the short period of time for which data on migration is available and the fact that this data includes short-term variations on migration flows, which may "hide" the long-term migration transition that each country would experience. However, this is a highly relevant factor in terms of climate change impacts on the economy: as a long-term phenomenon, climate change will have an increasing

[1] It has been suggested that the aspiration to migrate might also depend on the capabilities to afford migration, defining a concept of capacity to aspire (see ref. [26] and references therein.)

impact on the economic development of the countries, affecting the rate of progress along the migration hump. Moreover, assuming that countries follow the migration transition, it can be argued that the migration hump they would follow in the future is not the same as the one observed from the historical data, but rather adjusted on future levels of incomes. Some empirical results suggest that are relative values of real GDPc that define the migration hump[2] [46, 45]; other results, indicate that are actually absolute values of GDPc that shape aspirations and capability to migrate [55].

In order to cover the uncertainty coming from these open questions I test three alternative assumptions regarding the migration hump. The first assumption covers the case where the migration hump is a purely spatial phenomenon. By using average historical levels of GDPc I reproduce constant future emigration rates according to the observed migration hump. The second case assumes that countries undergo a migration transition with respect to their absolute real GDPc values. In this case I reproduce future emigration rates that follow the observed migration hump function as the GDPc of the country evolves. The third assumption considers a migration transition, as in the second case, but following a shifted migration hump in line with the change in global mean GDPc. This represents the case of the migration hump defined by relative values of GDPc. I name these three assumptions *CR* (constant rates), *T0* (transition with no change to the migration hump function) and *TS* (transition with shifted migration hump), respectively in the order I introduced them.

Using a recently developed international migration model I investigate how future climate change will affect migration, under each of these assumptions. Considering the highly complex interaction between climate change and international migration, this study focuses on the impact through one specific macroeconomic channel of impact: global warming impact on economic productivity. These results are not to be understood as predictions of future migration, but rather as a quantification of the effect of climate change on international migration via impacts on macroeconomic factors, while controlling for current uncertainties on the effects of these factors as main drivers of international migration.

4.2 Methods

4.2.1 Data

I use data on historical total population and bilateral migrant stocks (reported by place of birth and residence) from the UN Department of Economic and Social Affairs ([127],[169] respectively). Data on future projections of total population growth rates comes from the projections produced within the SSP scenarios [116]. In both cases the data is given at the country level.

Historical data on country-level GDPc is obtained from the Penn World Tables (PWT, [128]) version 8.1, which was expanded using the version 9.0 for including missing countries [129]. Data on future projections of GDPc comes from the SSP scenarios produced by the OECD [115].

[2]This means that a certain value of real GDPc would see that country on the increasing branch of the migration hump in the 2010s; while the same GDPc would see the country on the decreasing branch in the 1960s.

The source for the temperature data is a set of ten different Global Climate Models (GCM) (Appendix, Table C.1) [170]. The output of these models has been bias corrected within the Inter-Sectoral Impact Model Intercomparison Project ISIMIP [153]. Starting from country-level gridded data of temperature, I construct area-weighted average temperatures. Observed temperature data comes from the Climate Research Unit (CRU). For countries where temperature data was not available, the temperature of the closest country was used (Appendix, section C.1). It is important to specify that in my calculations, when I use absolute temperature data this comes only from observations while from the climate models only the differences in temperature are used.

4.2.2 Global warming impact on the economic productivity

Defining the period for a specific global warming level. I focus on the effect of future substantial global warming represented by two strong greenhouse gas (GHG) forcing scenarios, SSP3-7.0 and SSP5-8.5, which assume a radiative forcing of approximately 7.0 and 8.5 W/m^2 respectively, by the end of the century [132].

Both climate models and GHG scenarios differ in the speed of global warming. In order to control for these differences I focus on a specific level of 3°C global warming above pre-industrial conditions, rather than on a specific time period. Therefore the climate models in this case represent primarily the different possible spatial patterns of warming.

The 3°C level of global warming is expected to be reached in different periods for each scenario and climate model. To calculate this period I use a 30-year interval. The warming level at time t under the scenario s and the climate model m is defined as:

$$\Delta T_{t,s,m} = \Delta T_{t_{ref}} + \overline{T}_{t,s,m} - \overline{T}_{t_{ref},m}. \tag{4.1}$$

where t_{ref} is a period of reference corresponding to [1986-2005]. $\Delta T_{t_{ref}}$ is the observational global warming for t_{ref}, relative to pre-industrial conditions, and corresponds to 0.75°C [171].

$\overline{T}_{t_{ref},m}$ is the mean annual global temperature for the period t_{ref}, obtained from the climate model m. $\overline{T}_{t,s,m}$ is the same but for a 30-year period defined as $[t-14, t+15]$, where t assumes values on five-year intervals (i.e. at multiples of 5). $\Delta T_{t,s,m}$ =3°C defines the 30-year period of interest for each scenario and climate model (Appendix, Table C.1).

Global warming impact on GDPc. The effect of future global warming on migration is obtained through the indirect pathway of impacts on the GDPc. SSP-based GDPc trajectories represent the baseline on which the impact of global warming is calculated [115, 114]. In line with the GHG concentration scenarios introduced above, I focus on SSP 3 and 5. These two SSP narratives describe two very different futures in terms of economic development: SSP 3 assumes a relatively slow economic growth and a stagnant level of between country inequality; SSP 5, on the other hand, describes a future of strong economic growth and reduced between-country inequality.

Starting from these baseline projections of GDPc I calculate a perturbed version of each of them due to global warming. To this end I use two different methods from the climate-economic literature for calculating the perturbed trajectories [107]. The first method is the result of a cross-sectional approach, where long-term climate conditions are used to estimate the climate change effect on the economic productivity. The method accounts for adaptation to climate change and assumes that a specific warming level will produce the same impact in every country. On the other hand, the second method, describing the results from a panel regression analysis, focuses on short-term weather effects and does not consider adaptation strategies. Moreover, diverging from the previous method it assumes an impact that depends on the past climate conditions in the country and the impact has a non-linear dependency on the warming level: warmer countries would face a negative impact and cooler countries would benefit [107].

Following the two methods, I produce two alternative scenarios of GDPc for each of the two baseline trajectories of GDPc. The baseline trajectories are the ones prescribed by SSP 3 and 5 and the respective alternative trajectories are calculated by using the warming levels of GHG scenario SSP3-7.5 and 5-8.5, respectively.

Following equation 10 in ref. [107], the damage function on GDPc under the long-term impact method can be written as:

$$\ln(G^w_{t,i}) - \ln(G_{t,i}) = \alpha_T \Delta\tau_{t,i} \tag{4.2}$$

with α_T being a negative constant factor. $G_{t,i}$ and $G^w_{t,i}$ are the baseline and the perturbed GDPc, respectively, in the year t and in country i. The total warming is defined relative to the initial period 2011-2015: $\Delta\tau_{t,i} = \tau_{t,i} - \tau_{2015,i}$, where τ represents the averaged temperature during a period of five years, $\tau_{t,i} = \frac{1}{5}\sum_{l=0}^{4} T_{t-l,i}$, and $T_{t-l,i}$ are annual values of temperature.

The notation adopted in defining $\Delta\tau_{t,i}$ highlights two important aspects: the warming happening during a five-year period affects the GDPc at the end of the same; counterfactual GDPc trajectories start diverging from the baseline after the initial period 2011-2015. This means that, while I consider a global warming level of 3°C above pre-industrial conditions, the impact is calculated relative to a recent period, that has already experienced ~1°C of warming. Therefore, the impact considered here refers to the effect of additional 2°C of global warming.

Solving Equation 4.2 for $G^w_{t,i}$ gives the relation for producing projections of GDPc under global warming for this first method:

$$G^w_{t,i} = G_{t,i} \cdot e^{\alpha_T \Delta\tau_{t,i}}. \tag{4.3}$$

Equation 4.3 assumes that the warming will affect GDPc once and for all, at each time t, while in absence of further warming, the perturbed and baseline GDPc will be the same.
The second impact method focuses on the short-term weather variability. From equation S3 in the supplementary materials of ref. [107] the impact of global warming on the GDPc growth[3] can be written as:

$$\begin{aligned} \delta_{t,i} =& \alpha_1 \Delta T_{t,i} + \alpha_2 \Delta T_{t-1,i} + \\ & (\beta_1 \Delta T_{t,i} + \beta_2 \Delta T_{t-1,i}) \cdot \\ & \left(T_{0,i} + \sum_{j=1}^{t-1} \Delta T_{j,i} \right). \end{aligned} \tag{4.4}$$

[3]This is just the temperature-dependent component of the growth rate. The methods assume it possible to have a full disentanglement between a temperature-dependent factor and a second factor depending on all the rest.

α_1, α_2, β_1, β_2 are constant factors, estimated in ref. [107] and reported in Table 4.1. The method focuses on weather variability and therefore I use annual changes in temperature[4] ΔT. $T_{0,i}$ is the observed temperature in country i in the year t and $\Delta T_{0,i}$ is assumed to be zero. By definition the growth rate defined in Equation 4.4 links the baseline GDPc to the perturbed one through:

$$\ln(G^{w}_{t,i}) - \ln(G_{t,i}) = \sum_{l=1}^{t} \delta_{l,i} \tag{4.5}$$

which ultimately gives the relation for deriving the perturbed GDPc from the baseline:

$$G^{w}_{t,i} = G_{t,i} \cdot e^{\sum_{l=1}^{t} \delta_{l,i}}. \tag{4.6}$$

Importantly, in this second approach the magnitude of the impact depends on the past temperature changes. In other words, in this second approach the impact of the warming is path-dependent. This is important to keep in mind for when discussing the results, indeed the rate of warming is different between climate models and scenarios and would influence the impact on the GDPc.

4.2.3 Migration model and simulation

Defining the migration model. I use a global model of bilateral international migration that is calibrated on historical bilateral flow data and has been shown to represent well current patterns of migration (see also Chapters 1 and 2) [142].

The model defines the population by place of birth and residence. This specification allows the definition of three different types of migration: emigration from Country of Birth (CoB), transit between countries that are different from the CoB, return migration to the CoB. The latter have been shown to be an important component of the total migration flow, especially in some specific bilateral channels [104, 142].

The model produces bilateral international migration flows by using a small set of socio-demographic and economic factors recognised as important drivers of migration. For instance, it includes the network effect of the diaspora at the destination country, which can facilitate the process of migrating for new migrants, for example, by helping finding a job or an accommodation [119].

Economic factors, proxied by the GDPc, are also included in the model. In specific, the model accounts for the attracting effect of the destination GDPc and for the more complex dependence of migration flows on the origin GDPc. Indeed, emigration rates have been found to depend non-linearly on economic conditions at the origin country [44]; a behaviour that has been usually explained as a combination of intentions and capability to migrate [26, 44].

The migration model reads as follows:

$$M_{k,i\to j} = \begin{cases} a_j \cdot F(G_i)\, g_j^{\alpha_g}\, p_{k,j}^{\alpha_p}\, P_{k,i} & \text{if } k \neq j, \quad (4.7\text{a}) \\ b_i \cdot P_{k,i} & \text{if } k = j. \quad (4.7\text{b}) \end{cases}$$

[4] The previous method used differences on longer averages, i.e. five-year intervals.

$M_{k,i\rightarrow j}$ represents the number of migration moves per five-year period of people born in country k, living in i and moving to j. The migration from CoB ($k = i$) and the transit migration ($k \neq j$ and $k \neq i$) are both described by Equation 4.7a, while the return migration ($k = j$) is described by Equation 4.7b. In both cases the migration flow depends linearly on the number of people available to migrate $P_{k,i}$. a_j and b_i are country-specific scaling factors (the subscript defines the country). G_i is the GDPc at the origin country i, and $g_j = G_j/G_{glob}$ is the GDPc at the destination j, relative to the global mean GDPc, G_{glob}. $p_{k,j}$ represents a relative measure of the diaspora of k living in j and corresponds to $p_{k,j} = \frac{P_{k,j}}{\sum_l P_{k,l}}$. Worth to mention is the fact that in my model the diaspora acts directly and only on population of the same place of birth, rather than on the entire population living in their country of birth (this would include also migrants living in k).

Previous results have shown a strong proportionality between the migrant stocks and return migration flows [104, 142] and other studies show that return migration might have a weak dependence on economic conditions [120, 121]. Therefore, return migration flows are modelled simply as dependent on the migrant stocks available to migrate, scaled by a country-specific factor b_i.

The country-specific scaling factors provide a simple method for capturing various unobserved heterogeneities in the data. One very important factor that these parameters could capture are the immigration policies. Recent findings suggest that what matters the most for the migrants are the external regulations of immigration policies, that is the regulations posed for entering the country [36]. Pursuing the main aim of capturing the dependence on external regulations of immigration policies, I decide to include only origin-specific factors for return migration, and destination-specific factors for emigration from CoB and transit migration. This means that I assume that for emigration from CoB and transit migration, are the immigration policies at the destination country that matter. On the other hand, for return migration I assume that immigration policies at the destination have no impact since the migrants are entering their country of birth. On the other hand, immigration policies in the origin country would have an important role in refraining migrants, already living in the country, to return to their place of birth. The reason would be that migrants would worry about the possibility of re-entering the host country if they decide to leave [75].

The dependence of migration on the GDPc at the origin country enters the model only in the transit migration and emigration from CoB equation. The role of income levels, in this case proxied by the GDPc, on emigration is complex and has been observed to reproduce a migration hump shape, where the largest rates of emigration are observed from middle-income countries [44, 34]. This non-linear dependence can have different explanations [44]. One possibility would be that the migration hump emerges from the interplay between two factors: the intention and the capability to migrate [26]. Indeed, poverty constraints might limit the number of people that would eventually migrate, if they had the resources [50]. This would explain the low levels of emigration observed from very poor countries where the intentions to migrate would be high but the economic capability very low. On the other hand when countries are very rich the satisfaction of the population could be high, translating in weaker intentions to migrate. I try to capture this complex behaviour by using the superposition of two functions, one describing the intentions to migrate and the other describing the capability, both measured in terms of GDPc:

$$F(G_i) = \frac{1}{1+\frac{G_i}{\widehat{G}}} \cdot \frac{1}{1+e^{-\gamma(G_i-\widetilde{G})}}. \tag{4.8}$$

The relation between emigration rates and the intention to migrate is meant to be captured by the first term in Equation 4.8. Starting from the maximum of 1 when $G_i = 0$, it decreases to a minimum for large values of G_i. The second term is used to capture the dependence of emigration rates on the capability to migrate. It assumes a minimum for $G_i = 0$ and approaches the maximum of 1 for $G_i \gg \widetilde{G}$.

In order to control for impacts of future global warming on migration via macroeconomic impacts I need to consider how the relations between migration and the drivers introduced in the model, through Equations 4.7a, 4.7b and 4.8, will hold in the future. I assume that the effects due to the diaspora and the relative destination GDPc would remain at the level measured on observed migration flows.

Therefore my analysis focuses on the relation between emigration rates and income levels in the origin country, and on how this complex process could be transformed in the future. I test three different hypothesis. The first considers the case where the migration hump represents just a spatial pattern and does not imply that countries would change emigration rates according to it, as their GDPc changes [46]. Therefore in this first assumption I consider that future emigration rates hold constant to the values associated with the historical GDPc levels. In this case I calculate the emigration rates by evaluating Equation 4.8 at the mean historical GDPc value, where the historical period is from 1990 to 2015. I refer to this case as *CR*, for constant rates. The second hypothesis assumes that the migration hump describes a temporal dynamics as well as a spatial pattern [45]. In this case I assume that countries undergo a migration transition as their economy develops. Emigration rates are obtained by evaluating Equation 4.8 at the future levels of GDPc. I refer to this case as *T0*, for migration transition, no change to the migration hump. The third assumption considers the case when countries undergo a migration transition, but it happens on a different migration hump function, which is redefined on the future distribution of GDPc. This means that emigration rates react following a migration hump function but in terms of relative GDPc. I assume that the shift follows the growth rate[5] r of the global mean GDPc:

$$r = \frac{\overline{G}_{hist}}{\overline{G}_{proj}} - 1, \tag{4.9}$$

where $\overline{G}_{hist}$ and $\overline{G}_{proj}$ represent the global mean GDPc for the historical period and the period of interest (3°C global warming) respectively. Redefining the GDPc as $G_i \to G_i \cdot (1+r)$, where $r < 0$, and substituting it in Equation 4.8 produces a shifted and dilated version of the historical migration hump:

$$F(G_i) = \frac{1}{1+\frac{G_i\cdot(1+r)}{\widehat{G}}} \cdot \frac{1}{1+e^{-\gamma(G_i\cdot(1+r)-\widetilde{G})}}. \tag{4.10}$$

[5]Since I am looking at the growth rate that would explain the change from the projected GDPc to the historical one, follows that $r < 0$, representing a de-growth.

The transformation uses the same rate r for all GDPc points, this produces, in absolute terms, a shift that depends on the specific value of GDPc and corresponds to: $G_i \cdot r$.

In order to obtain projections of migration flows using the migration model described above, data on future bilateral migrant stocks, under the SSP scenarios, is needed. SSP scenarios provide only data on future country-level total population and growth rate, not broken by place of birth. Therefore, I produce projections of bilateral migrant stocks using the SSP based growth rate of the total population. Starting from the observed data on bilateral migrant stocks in the year 2015 I construct future projections of population stocks defined by place of birth and residence following the recursive Equation 4.11:

$$P_{i,j}(t) = P_{i,j}(t-1) \cdot (1 + \rho_i) \tag{4.11}$$

using, as for the migration model, a five-year step; $P_{i,j}(t-1)$ is the population born in i and living in j at time $t-1$; and ρ_i is the five-year growth rate of country i as prescribed by the SSP scenario.

Simulation. I calculate bilateral migration flows for 177 countries and for each interval of five years within a period of 30 years (period of interest). I produce these flows by evaluating Equations 4.7a and 4.7b at the first year of each five-year interval within the period of interest. This set of estimations is produced for the baseline GDPc trajectory as well as for perturbed trajectories of GDPc, that is for each global warming impact method (2 methods) climate model (10 models) and SSP scenario (2 scenarios). Finally, each of these sets of estimates is reproduced separately for each of the three assumptions regarding the migration hump function: *CR*, *T0* and *TS*.

The period of interest, in principle, differs between climate models and scenarios. This would make the results not fully comparable in the sense that the impact on migration would depend on the population distribution in the specific period. Since I want to isolate the effect of global warming on migration through the GDPc factor, I select one period of interest to use for all the simulations. It corresponds to the averaged value between the periods of interest obtained for the different climate models and scenarios: [2046-2075].

The values of the parameters used for the climate change impact on GDPc come from ref. [107]. The values of the parameters used for the migration model have been obtained in subsection 3.2.4. Table 4.1 collects the global parameters for both the migration model and the impact methods. Country-specific scaling factors are reported in Table C.2.

Table 4.1: Migration model and climate change effect parameters.

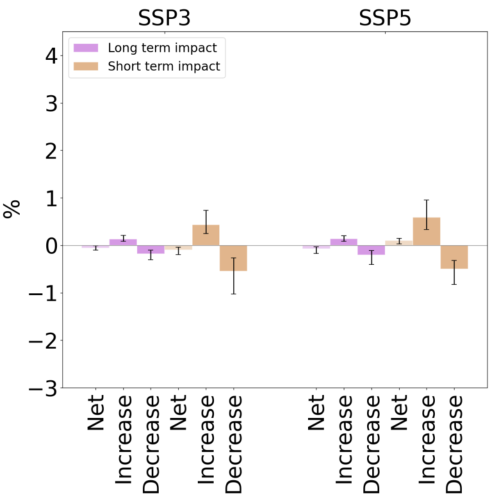
Variable	*Parameter*	*Value used*
Emigration and transit migration		
Intercept	a	0.233
Diaspora	α_p	0.943
Dest. GDP	α_g	0.19
Orig. GDP	γ	-0.0016
	$\widehat{G}$	\$ 35301
	$\widetilde{G}$	\$ 929
Return migration		
Intercept	b	0.124
Climate change effect on GDP		
Cross-sectional	α_T	-0.023
Panel	α_1	0.00641
	α_2	0.00345
	β_1	-0.00109
	β_2	-0.000718

Global parameters for both the international migration model and the climate change impact methods.

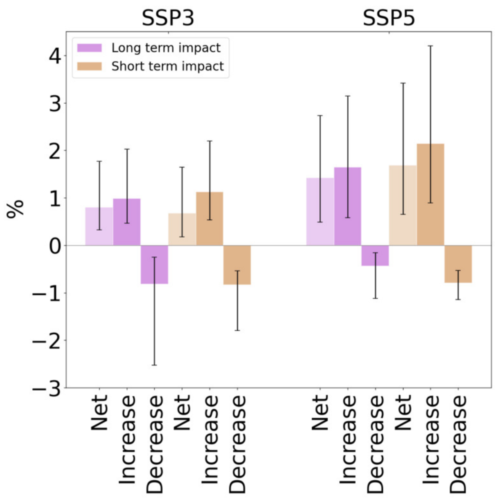
The analysis is constructed by separating the estimates in three different subsets corresponding to the three assumptions about the migration hump. Within these subsets I separate the two SSP scenarios and for each of them I compare the estimates obtained from the baseline GDPc trajectories to the estimates obtained from the perturbed GDPc. All estimates are averaged on both the temporal and climate models dimension.

4.3 Results

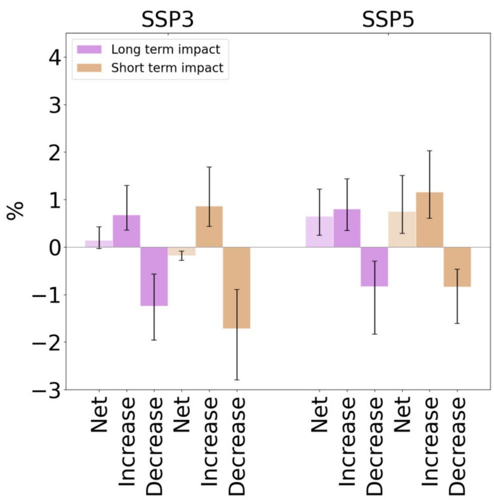
Starting from the most aggregated level, i.e. global migration flow, under the *CR* case, I find that climate change impacts would produce a net decrease in the total number of movements, except for the case of SSP5-8.5, short-term method, where the net result is positive ($\sim 0.1\%$, on average and per five-year period) (Figure 4.1a, light-coloured bar). Importantly, aggregating the results in terms of net migration differences does not provide a comprehensive overview of the impact of climate change. In the *CR* case the only difference between the baseline estimates and the ones under perturbed GDPc is in the destination GDPc term, which enters the model in relative terms of the global mean GDPc. Therefore, when climate change produces a negative impact on the economy of a country, the result in terms of migration impact is divergent: it decreases migration to the country if the losses that the country faces are larger than those of the global mean GDPc, it increases immigration otherwise. Therefore, along with the net change in global migration I consider separately the total number of flows that would be affected by climate change, either being inhibited or induced. Under the *CR* case, these two quantities are similar between them, for all impact methods and scenarios (Figure 4.1a, dark-coloured bars), and sum up to the total number of impacted flows reaching a maximum of $\sim 1.1\%$ under the short-term method.



(a) CR



(b) T0

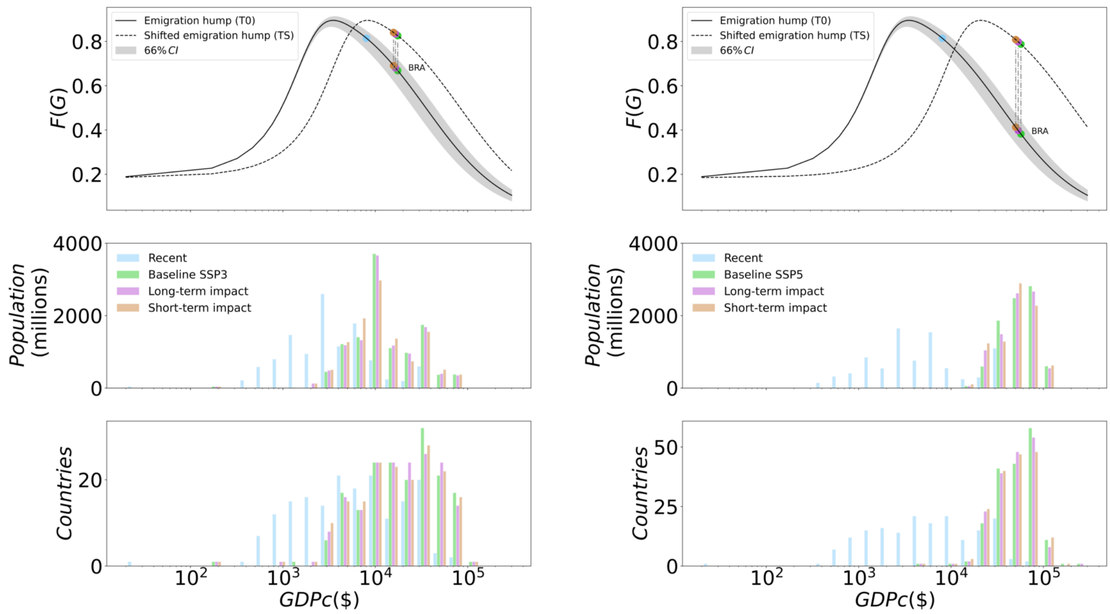


(c) TS

Figure 4.1: Difference in global migration movements between the climate change scenario and the baseline. Values are expressed in percentage relative to the baseline case. Positive values define an increase under the climate change scenario compared to a future without the climate change impact. The impact in terms of increased, decreased and net flows are shown separately. Each sub-figure collects results for one specific assumption about the migration hump. Flows represented are averaged over the 30-year period of interest and the ensemble of GCMs. Error bars represent the extremes reached within the ensemble of GCMs.

When I consider the *T0* assumption I find larger and positive net differences of global migration, for all scenarios and impact methods (Figure 4.1b, light-coloured bar). Reporting separately inhibited and induced flows remains important under the migration transition hypothesis associated with the *T0* case. Indeed, economic losses due to the warming impact, would push the countries towards lower levels of GDPc, which are associated with lower emigration rates in the increasing branch of the migration hump (Figure 4.2, top panel, black line). As for the previous case, the number of total affected flows, summing up the decrease and increase, remains larger than the net figure, reaching a peak of $\sim 3\%$ (Figure 4.1b, dark-coloured bars). The *TS* case produces results somewhere in between the *CR* and *T0* case, showing a larger impact compared to the first but smaller than the second case (Figure 4.1c).

Interestingly, in this case under SSP3-7.0 a divergent result is shown for the two methods of impact.



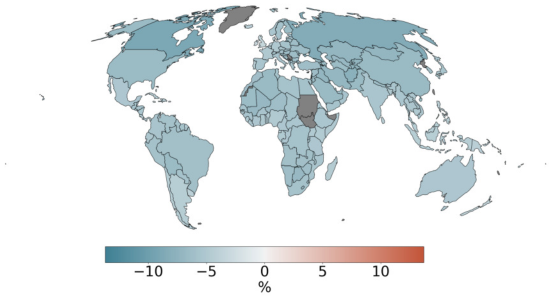
(a) SSP3-7.0

(b) SSP5-8.5

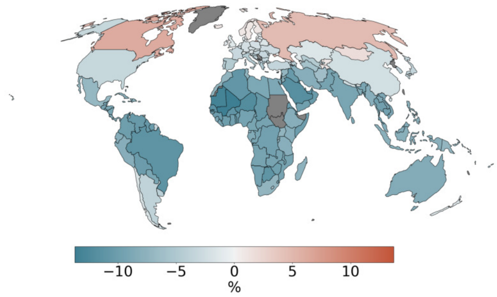
Figure 4.2: Migration hump function, countries and population weighted GDPc distribution. The upper panel shows the migration hump function for the *T0* assumption (black line), and its shifted version for the *TS* assumption (dashed line). The location of a country on both these curves and its location under the *CR* assumption (blue dot), is shown. Grey area represents the extremes reached by the migration hump function when considering the parameter $\hat{G}$ on its values at 66% confidence interval (see subsection 3.2.4). The middle panel shows the population weighted GDPc distribution, for the baseline scenario, for both climate change impact methods and for the *CR* assumption. Population and GDPc are averaged for the 30-year period of interest and over the climate models dimension. The bottom panel shows the same as the middle panel but for the number of countries instead of the population.

Altogether the results suggest that: short-term impact produces larger differences in migration compared to the long-term impact method; the *CR* assumption leads to smaller differences in migration compared to the two cases that assume migration transition, i.e. *T0* and *TS*; the largest differences are produced under the *T0* case. These results can be understood by referring to the functional form of the migration model and climate change impacts.

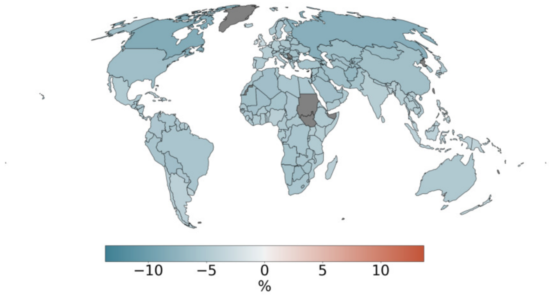
The larger differences in migration under the short-term method compared to the long-term method can be explained as follows. The short-term method produces divergent impacts on the economy of the countries, with some countries even gaining from the global warming impact; when impacts are on the same direction, between the two impact methods, the short-term method leads usually to larger damages (Figure 4.3). Under the *CR* assumption, the only difference between the baseline and perturbed case is in the relative destination GDPc. Since this quantity is defined in terms of global mean GDPc, the impact under the long-term method, which assumes negative impact for all the countries, might be small compared to the short-term case where the impact of climate change is asymmetric, with some countries even benefiting from the global warming. Indeed, this would result in increasing the gap of GDPc between



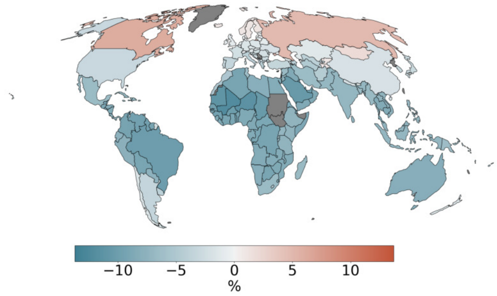
(a) SSP5-8.5, long-term impact method



(b) SSP5-8.5, short-term impact method



(c) SSP3-7.0, long-term impact method



(d) SSP3-7.0, short-term impact method

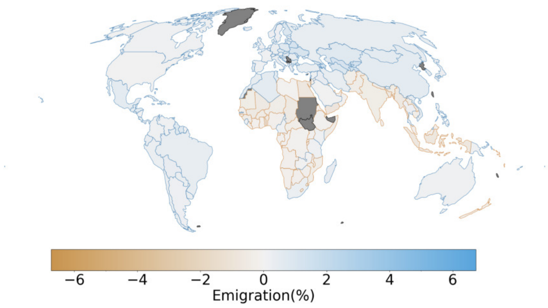
Figure 4.3: Country level, climate change impact on GDPc. Positive values represent increase in GDPc under the climate change impact case. The change is calculated as relative to the baseline scenario without climate change impact. Values represent the mean reached within the period of interest. Values represent the average along the climate models ensemble and period of interest dimension. Panels (a) and (b) show the long-term and short-term impact method respectively.

countries, reinforcing immigration to those countries that see an increase in GDPc larger than that experienced by the global mean GDPc, and a decrease of immigration otherwise. Results show that this diverging effects would cancel out in terms of net differences but the underlying effect in terms of increases and decreases is substantially larger under the short-term method (Figure 4.1a). Under the *T0* and *TS* assumptions, a larger economic impact under the short-term method compared to the long-term case would act also through the origin country GDPc and the migration transition, pushing the countries towards lower levels of GDPc, which are associated with higher rates of emigration, if the country is on the right branch of the migration hump (Figure 4.2, top panel, black line).

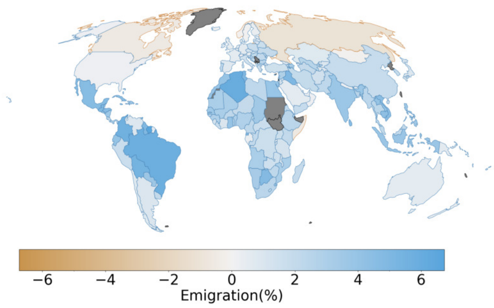
The role of the origin GDPc appears relevant, as can be observed by comparing the results from *T0* and *TS* to those obtained from *CR*. The difference is important also between the *T0* and *TS* cases and is due to the fact that the shifted emigration hump has a larger number of countries and population close to its peak, compared to the *T0* case. This is a region of GDPc values where the shifted migration hump is less steep than the *T0* case. Therefore, the same change in GDPc in this region would produce a smaller effect on migration under the *TS* case than the same change would produce on the original non-shifted function (Figure 4.2).

For clarity I focus now on SSP5-8.5 and the short-term impact method. Corresponding results for SSP3-7.0 can be found in the appendix. At the country level results mirror those observed at the global level. Under the *CR* assumption, emigration is projected to increase due to climate change in many regions (Figure 4.4a). Exceptions are various countries in Africa and Southeast Asia. Since under this assumption the impact of climate change acts only through the relative destination GDPc factor, it follows that the major emigration from these regions has a destination country where the loss in GDPc due to climate change is larger than the loss observed at the level of global mean GDPc.

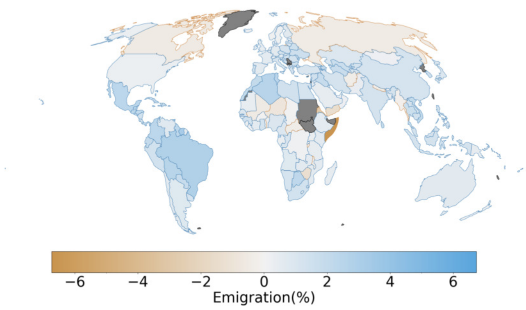
Under the *T0* and *TS* assumptions emigration is projected to increase for many countries, including most of those in Africa and Southeast Asia that under the *CR* assumption are projected to see a decrease in emigration (Figures 4.4b and 4.4c). This highlights the fact that, under my model, origin GDPc has a larger impact on migration compared to the destination GDPc.



(a) CR



(b) T0

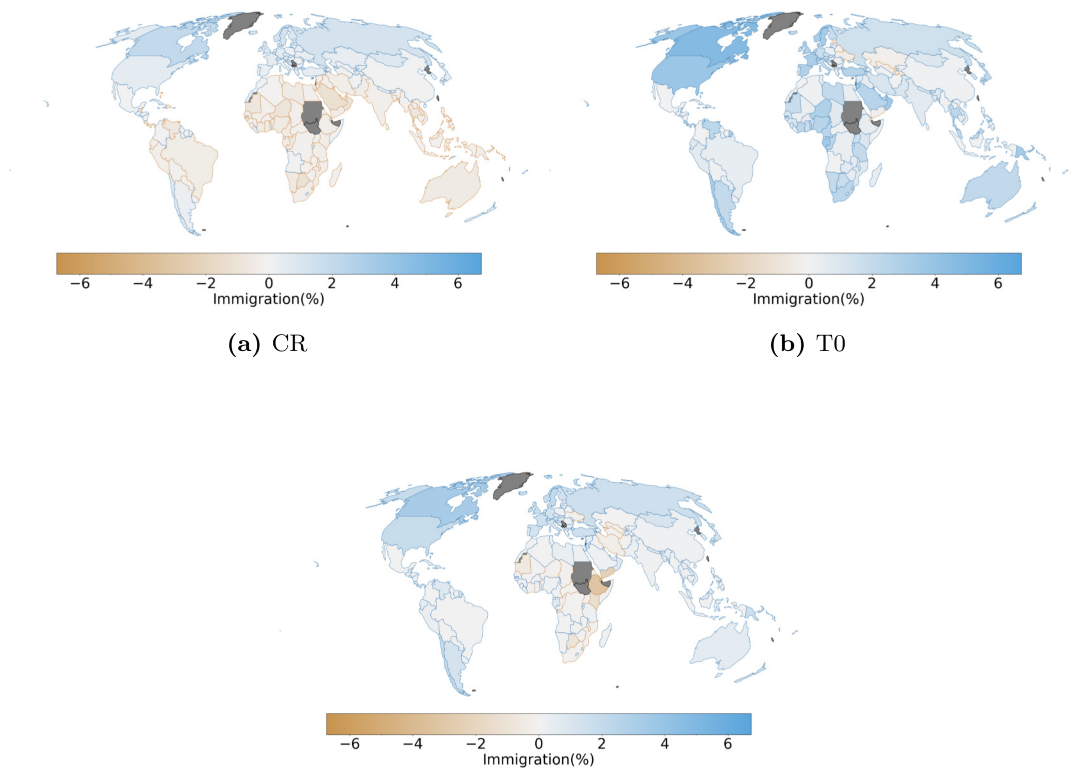


(c) TS

Figure 4.4: Country level, climate change impact on emigration under SSP5-8.5 scenario and short-term impact method and for the three different assumptions regarding emigration rates. Positive values represent an increase in emigration under the climate change impact case and is expressed in relative terms of the baseline case. Flows represent five-year moves, averaged on the 30-year period of interest and on the climate models dimension.

The differences in emigration observed in these two cases are predominantly explained by the spatial pattern of economic impacts applied to the two migration hump functions. Under the *T0* case, all countries have crossed the peak of the migration hump, therefore a loss in GDPc will move them towards higher rates of emigration, while gains due to the climate change impact will take them further to the left-end, reducing their emigration rates (see Canada in Figure 4.4b). Under the *TS* case the process driving the change in emigration is the same. Since in this case the migration hump has moved together with the change in the global mean GDPc, some countries may find themselves on the left branch of the hump and therefore a loss in GDPc due to climate change will result in lower emigration rates (see countries in Africa in Figure 4.4c).

Immigration, under the constant emigration rate assumption *CR*, resembles, for many countries, the pattern of economic impacts (Figure 4.5a).



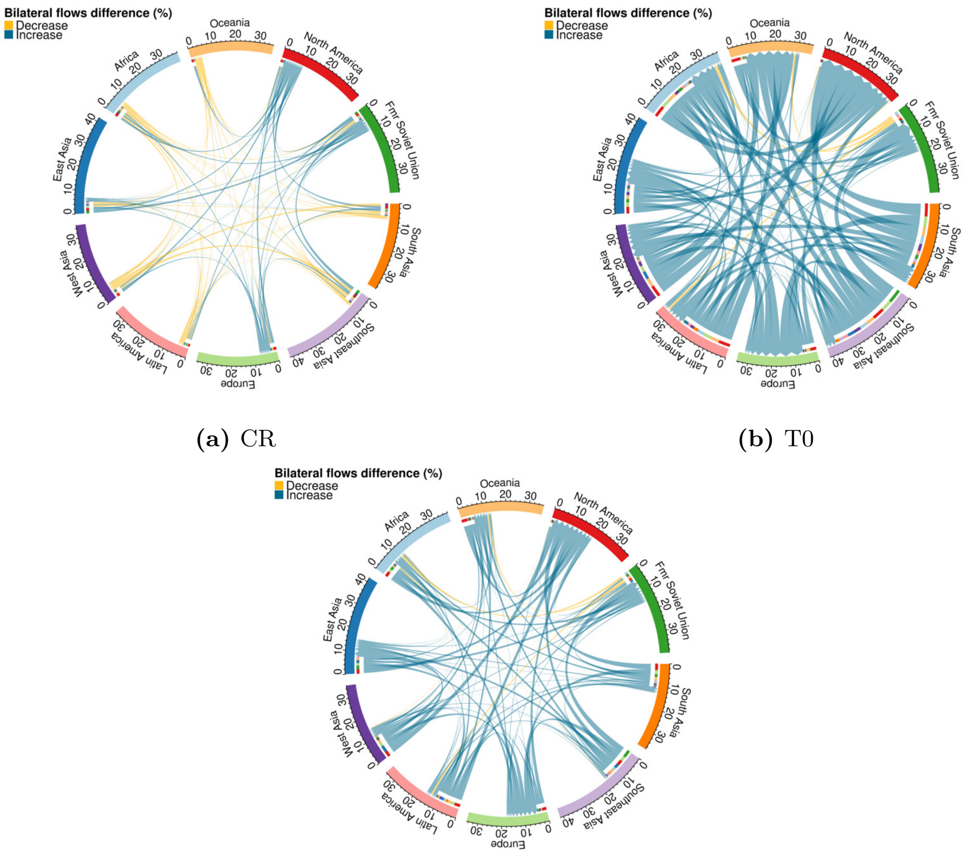
(a) CR **(b)** T0

(c) TS

Figure 4.5: As in Figure 4.4 but for immigration.

Escaping from this pattern there are countries where immigration increases despite the negative impact. One explanation would be that, even facing an economic loss in absolute terms, the result, in relative terms of global mean GDPc, would be positive. Another explanation would come from the fact that the model accounts for return flows, which do not depend anyhow on economic factors. These flows may be large for specific bilateral channels, e.g United States to Mexico, and substitute the effect of a reduced GDPc in the destination. Under the migration transition hypothesis *T0* and *TS* I find that immigration is projected to increase for most of the countries, despite the negative economic impacts of climate change (Figures 4.5b and 4.5c). This highlights the fact that under a negative impact of climate change, the push factor of economic losses at the origin would compensate for a reduced attractive power of destination countries. This would suggest a more complex pattern of reaction of migration to climate change impacts than assumed by a simple assumption where migrants would leave countries affected negatively from climate change for moving to countries that benefit from it.

Finally, exploiting the bilateral dimension of the migration flows calculated from the model I consider the difference in the bilateral flows between ten major world regions (Figure 4.6). These figures are constructed by summing up the country-level bilateral flows along the respective world region (Appendix, Table C.2).



(a) CR

(b) T0

(c) TS

Figure 4.6: Impact of climate change on bilateral flows between and within ten major world regions. Each subplot refers to the SSP5-8.5 scenario and short-term impact method. Each of them represents one of the three assumptions regarding the emigration rates dependence on origin GDPc. The reported values represent, in percentage, the difference between the climate change case and the baseline, in relative terms of the baseline case. Positive values identify the cases where migration under the climate change impact scenario is larger than in the baseline scenario. The external thicker arc defines the region of origin and the smaller internal arc shows the region of destination. Arrows point to the destination region. Flows represented are averaged along the climate models and time dimension.

These aggregated flows are calculated for each scenario, climate model, impact method and emigration rates assumption. Following the method exposed above for discussing the country level and global results, these regional-level flows are averaged along the temporal dimension of the period of interest and along the climate models. I calculate then the difference between the climate change output and the baseline, for each regional bilateral flow. Under the *CR* assumption, in line with the results at the global level, the effect of climate change on regional bilateral flows is overall small and shows a mixed pattern of increase and decrease. In specific, rich regions like Europe and North America would see an increase in immigration from all the other regions (Figure 4.6a). Under the assumptions of migration transition *T0* I find larger effects on both between and within regions bilateral flows (Figure 4.6b). Interestingly, migration increase not only along the existing migration routes from poor to rich regions, but also in between poor regions like Asia to Africa. Since these figures are expressed in relative terms, even small differences in absolute terms could appear substantially large. When I report the same figure but in terms of absolute differences between the perturbed and baseline cases, it becomes visible that the largest changes in poor regions like Africa are due to internal migration (Appendix, Figure C.2). Similar results, but at a lower level, are found for the *TS* assumption (Figure 4.6c).

Under the migration transition assumptions *T0* and *TS*, results show, at all levels of aggregation, larger increasing flows of migration due to climate change impacts than compared to the *CR* case. This highlights the fact that, under my model assumptions, economic constraints at the origin country play a major role in inhibiting migration movements and in general in defining the patterns of both emigration and immigration.

4.4 Discussion

The effect of projected global warming on the economic productivity of the countries rises a relevant concern about how these effects will in turn influence future patterns of international migration. Specifically, in the case that countries undergo a migration transition process, global warming effects, in terms of economic losses or gains, will accelerate or slow down the transition, affecting the long-term trend of migration patterns. The paucity of migration data does not allow for a robust validation of this hypothesis. This last part of my study is a first attempt to overcome this limitation by producing a wide range of potential outcomes under assumptions that would cover different uncertainties deriving from this limitation. Using a recently developed model for international migration and two methods for estimating economic impacts of global warming, I investigate the effect of a scenario of 3°C global warming above pre-industrial levels on the spatial patterns of international migration. Due to the complexity of interactions between climate change and migration I focus on one specific pathway of macroeconomic impacts, controlling for different assumptions on the migration transition process.

Results suggest that climate change may produce an appreciable impact on international migration flows, even in absence of migration transition (*CR*). In this case, macroeconomic impacts redefine the economic attractiveness of the countries for immigration, producing appreciable net differences in migration moves at different spatial scales of resolution. The effect becomes substantially larger if I consider all the affected moves, inhibited and induced, rather than the net difference. This suggests the relevance of measuring the impact on migration by using quantities that go beyond the net effects. The impacts on migration become larger when the migration transition process is included. The largest impact is observed when the migration transition follows the migration hump relation estimated from the historical data (*T0*). Smaller values, but still larger than in the *CR* case, are observed for the migration transition following a migration hump shifted on future levels of income (*TS*). Importantly, the results under the different assumptions on emigration rates highlight the fact that poverty constraint is a major factor reducing global mobility.

While both, the method of global warming impact on GDPc and the migration model, represent an improvement on previous approaches, my results suffer from limitations applying to both of them. The methods for calculating the economic impact expand on previous studies [106, 161] by improving both the temporal and spatial resolution of the analysis [107]. On the temporal scale this allows for distinguishing between weather variability (annual scale) and climate impacts (decades scale). On the spatial scale, the sub-national resolution of the analysis allows for including country fixed effects in the cross-sectional analysis, an important limitation of previous studies. Despite the improvements, these methods follow the majority of previous studies [162, 172, 163, 164, 165, 108], by considering only the effects of climate change through the temperature variable. Recently has been shown that the macroeconomic impacts would materialize also from the change in precipitations [109]. Therefore my results, focusing only on the temperature as the vector for transferring the impact of climate change on international migration, should be considered as a possible range of outcomes, but not a complete one.

The migration model represents an important innovation compared to previous approaches. Accounting directly for return migration and the non-linearities associated with the emigration-incomes relation, the model allows for investigating their role in projections under future global warming. Nonetheless, the model uses projections of bilateral migrant stocks derived by using country level rates of natural population change. This method does not account for adjustment effects due to the migration flows happening from the historical period to the period of projections. This effects would need to be accounted for in order to produce a quantitative prediction. Nonetheless should also be recognised that such limitation is observed in all the gravity-type migration models [155].

Another important limitation of the model is the absence of quantities capturing the within-country income distribution, i.e. inequality, and its change. The change in within-country income distribution most likely will depend also on climate change. Immigration policies are important factors shaping international migration. Here I try to include them through the country-specific scaling factors. Nonetheless this approach does not allow for an explicit attribution of the effect of immigration policies on future migration. Implementing these dimensions of heterogeneity will be an important direction of future development of this analysis.

Despite these limitations, the results show, for the first time, the potential impact of future climate change on international migration, globally and through one specific macroeconomic variable (temperature). The results should be interpreted as a step towards a more comprehensive and mechanistic approach for quantifying climate change impacts on international migration. They also should serve to inform future model development and data analysis regarding both the climate change impacts and international migration.

5

Conclusions

The aim of this doctoral research has been to investigate the response of international migration to climate change impacts. To this end I have proceeded in three steps which are represented by the three chapters of this dissertation: first I have built a mathematical model for reproducing bilateral international migration flows; in a second step I have used this international migration model for producing a first quantification of recent international migration flows attributable to climate change impacts; in a last step I have used the international migration model for producing estimates of future international migration flows that would be affected by projected global warming scenarios.

Previous studies that have produced projections of international migration flows are usually affected by different limitations that can be identified, among others, by the restricted number of countries that they include; the absence of an explicit dependence on factors identified as drivers of migration; the aggregated level of migration flows and the simplistic assumptions based on economic theories which assume people migrating in order to maximize incomes.

In the first part of my research I have developed a model that overcomes these limitations and represents an unprecedented tool for the complexity of the processes that it includes, the explicit drivers that it uses and its spatial coverage and resolution, while remaining simple enough for a transparent and mechanistic interpretation of the results.

Indeed, the model reproduces international migration flows at the global level covering more than 170 countries and potentially even more if not constrained by data availability. By defining the population by place of birth and residence it can reproduce one migration flow for each combination of country of birth - country of origin(residence) - country of destination. Therefore, it can account separately for transit and return flows. The latter being very important in some specific channels from richer to poorer countries [103]. The model accounts explicitly for socio-demographic and economic factors that shape migration flows. For instance, the model includes the role of diaspora in the destination country as attractor of new migrants. Indeed, both migration theories and empirical results suggest that the role of the diaspora at the destination plays a substantial role in reinforcing immigration flows [35, 18]. The model accounts for this process by letting the diaspora attract new migrants from the same place of birth. Economic conditions, proxied by the GDPc, at both origin and destination country are also included explicitly in the model. In specific, economic conditions at the destination enter the model in relative terms of the global mean GDPc, reproducing a crude process of decision about the destination country, informed on the global economic status. I have included the dependence of emigration rates on economic conditions at the origin country by following robust empirical results that find a hump shaped function linking these two quantities: it assumes low levels of emigration rates from low- and high-income while the highest levels of emigration rates are assumed from the middle-income countries [44]. I have assumed here that the migration hump describes not only a spatial relation but also a temporal one, termed migration transition: countries track the prescribed migration hump function as their economic development proceeds [45]. In including the migration hump function in my model I have gone a bit further than just introducing a function that reproduces it. Following the migration theory of intentions and capabilities I have specified the dependence of emigration rates on two terms that try to capture the dependence of both, the intention and capability to migrate, on values of GDPc at the origin [26]. This is a major innovation considering previous studies. Indeed, by assuming that the migration hump emerges as a combination of intentions and capabilities, I can interpret my results not only in terms of who migrates but including also that portion of population that would migrate but is trapped by economic conditions insufficient for migrating internationally.

In the first part of my research I have used the migration model within a dynamic population model where the population stocks are updated iteratively on intervals of five years by the number of births, deaths and net migration flows calculated for that same interval of time. I have used this dynamic simulation in the first part of my research for producing hindcasts and projections of international migration flows and population stocks [142]. My results show that the model, while being parsimonious in the number of explanatory variables, can reproduce well past net migration trend in many regions and countries. The projections, produced under different SSP scenarios of GDPc, highlight the key role of income levels and between-country inequality paths that differentiate the SSP trajectories. In particular, a scenario like SSP 3 characterized by regional rivalry and economically stagnant leads to high levels of net emigration at the end century in many countries and regions. Conversely, in a scenario like SSP 5, characterized by reduced between-countries inequality and rapid economic growth, my model projects net migration flows that approach zero at the end of the century. The model also highlights the inertia of the diaspora feedback, which, under a counterfactual scenario of constant country-specific GDPc values produces monotonous increase in emigration flows. The model still suffers from different limitations such as not being able to capture abrupt extreme events of migration flows caused by calamities such as wars and global financial crisis. Also, the model, while reproducing well the trend and level of net migration flows in many regions and countries, is not able to capture short-term variations of migration flows, as is the case for all the gravity-based international migration models [155].

In the second part of my research I have employed the migration model for investigating the impact of climate change on recent international migration flows, globally. Estimating the number of people that have migrated due to climate change is a difficult task. Indeed the chain of causes and effects that from the climate change impact leads to the migration decision might be very complicated. In order to overcome this difficulty I have suggested here to look at the effect of climate change on migration via its impacts on the economic productivity of the countries. Indeed, climate change impacts have already pervaded not only natural systems but also human-made systems. In particular, empirical results have found that climate change has already increased global economic inequality [110]. Applying two different methods from the climate-economics literature for calculating the impact of climate variation and weather variability on the economic productivity of the country, I have produced counterfactual time-series of GDPc for a past without global warming. I have used these counterfactual economic conditions as input to my international migration model for producing counterfactual estimates of international migration flows, globally and for a recent period of three decades. These counterfactual migration flows, compared to those calculated by using historical (factual) GDPc data, produce an estimation of the potential role that climate change might have had in conditioning international migration flows. I have found that the effect of climate change on international migration patterns, via the impact on the economic productivity of the countries, might have been small but significant. Importantly, by accounting for non-linearities in shaping emigration rates in relation to origin economic conditions, I find a divergent effect of climate change on migration: international mobility has been inhibited from poorer regions while it has been reinforced in richer regions. This result is "hidden" when I look only at the actual difference in migration moves between the counterfactual and factual case, but it emerges when I consider separately the flows that might have been inhibited and those that might have been induced by the climate change impact. This pattern is explained mainly by the functional form of the migration hump function assumed in my model and the migration transition process. Indeed a loss in terms of GDPc due to climate change impacts would move a country towards lower levels of GDPc which, in terms of the migration hump, would be associated with lower levels of emigration rates, if the country has not crossed the peak of the migration hump, while it would produce an increase in emigration rates if the country has already crossed it. In this second part I have produced a first quantification of the impact of climate change on recent global international migration patterns by focusing on one specific channel of transmission of the impact, the economic productivity, and one specific climate variable, the temperature, capturing the climate change phenomenon.

In the third part of my research I have used my international migration model for studying the effect that a future scenario of 3°C global warming above pre-industrial conditions would have on international migration patterns. To this end I have used the same methods employed previously for estimating the impact of global warming on the economic output of the countries. Hence, starting from baseline trajectories of country-level GDPc, as prescribed by the scenarios SSP 3 and SSP 5, I have calculated perturbed trajectories under future greenhouse gas (GHG) concentration scenarios, SSP3-7.0 and SSP5-8.5 respectively, and an ensemble of ten global climate models. Since I consider a specific warming level, the difference between climate models lies mainly in the spatial patterns of warming, and the difference in the GHG scenario lies in the different rate of warming. Both the GHG scenarios and the climate models serve in my case for accounting for the uncertainties related to the projections of global warming. The baseline trajectories and the perturbed ones enter my international migration model and produce estimates of international migration for the period of time associated with the 3°C global warming level. On the other hand, uncertainties in the migration model are investigated by considering different assumptions about the migration hump function. In specific, I test three assumptions: the first considers the migration hump as describing purely a spatial relationship between emigration rates and GDPc in the origin. This means that in the first assumption emigration rates are constant for each country and equal to the level associated by the migration hump function to the historical mean income level of the country. The second case assumes that the migration hump does actually describe a migration transition. In this second case countries change their emigration rates according to the levels prescribed by the migration hump, as their GDPc changes. The third assumption considers that the migration transition happens but on a shifted version of the migration hump. I have shifted the migration hump following the growth of the mean global GDPc between the historical and future period of interest, where the 3°C global warming is reached. This means that I consider relative, rather than absolute, levels of GDPc defining the migration hump. I have compared then, for each of these assumptions, the migration flows obtained from the perturbed trajectories of GDPc to those obtained by using the baseline trajectories. My results suggest that future global warming, by impacting the economic productivity of the countries, will affect substantially the international migration patterns by increasing the net number of migration moves. In terms of my model specification this is explained by the fact that, climate change by slowing down the economic development of the countries will keep them on levels of GDPc associated with higher levels of emigration rates. Impacts are larger under the cases that assume migration transition than under the case of constant emigration rates. This suggests that poverty constraints are major factors inhibiting international mobility. On the other hand, the effect, even if smaller, remains significant under the constant emigration rate assumption. In this case, climate change, by impacting differently the economic output of the countries would act to reorganize their attractiveness in relative terms of global GDPc. Importantly, the number of affected migration moves, while small in net terms, becomes larger and significant when I consider separately the inhibited and induced flows. This is a very important point because it appears fundamental not only under the assumptions of migration transition but also under the case of constant emigration rates: the magnitude of the impact of climate change when I consider separately inhibited and induced flows is usually twice the magnitude found when considering the net change in migration moves.

The model that I have developed as well as the methods for estimating the impact of climate change suffer from different limitations. The migration model does not account for important factors shaping international migration as can be immigration policies, neither does it include within-countries income differences or changes of these. The model is also not able to capture the temporal dynamics of bilateral migration flows, this is important for producing predictive estimates of international migration where dynamic adjustments and feedback processes are included. Nonetheless, while these are limitations that affect all the gravity based models, my model provides a novelty in accounting for the heterogeneities and processes outlined above. Also, assuming that its dynamics is driven by the long-run of the processes that it includes and thought to describe international migration, the model, in its dynamic version, can still be used for producing scenarios of international migration.

The methods used here for calculating the climate change impact on international migration provide a relatively simple method for connecting climate change to international migration: connecting the two phenomenon via the economic channel is intuitive and both the nexus climate change-economic effect and economic conditions-migration are well based in the theory and in the empirical results. Still, the methods applied here use only the temperature as a climate variable for transferring climate change impacts. Recently has been shown that precipitation as well captures well the economic impacts of climate change [109]. Nonetheless the methods that I have used here, by focusing on one specific channel of impact, that is macroeconomic impacts, and one specific climate variable, the temperature, makes my study transparent and compatible with future studies.

Overall, the results of my research have provided a first step towards a more mechanistic understanding of the pathway that from climate change leads to international migration. My results have shown that for a better understanding of the effects of climate change on international migration we need to go beyond figures of net migration moves and consider also the migration moves that would be inhibited due to climate change impacts. This aspect becomes fundamental when we assume not simplistic economic drivers shaping migration but more complex processes that account for conditions that constrain people from migrating.

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Appendix A

A.1 Text

The following list includes the countries and territories (in descending order by population in 2015) that are not used in my dynamic model, due to missing data:

- Sudan, Dem. People's Republic of Korea, South Sudan, Timor-Leste, Réunion, Micronesia, Guadeloupe, Martinique, China Macao SAR, Western Sahara, French Polynesia, New Caledonia, Curaçao, Channel Islands, Guam, French Guiana, United States Virgin Islands, Grenada, Mayotte, Kiribati, Dominica, Seychelles, Isle of Man, Antigua and Barbuda, Aruba, Bermuda, Greenland, Andorra, Faeroe Islands, Marshall Islands, American Samoa, Northern Mariana Islands, Saint Kitts and Nevis, Monaco, Gibraltar, Liechtenstein, Sint Maarten (Dutch part), Cayman Islands, San Marino, Cook Islands, British Virgin Islands, Palau, Wallis and Futuna Islands, Turks and Caicos Islands, Montserrat, Nauru, Tuvalu, Anguilla, Saint Pierre and Miquelon, Saint Helena, Niue, Falkland Islands (Malvinas), Tokelau, Holy See.

A.2 Table

Table A.1: First 30 largest bilateral migration flows in the A19 dataset, where the ratio of GDPc (origin/destination) is larger than 2. Flows are aggregated over the entire period 1990–2015, while the GDPc ratio is the average during the same period.

Origin	Destination	Flow (in millions)	GDPc ratio (origin/destination)
USA	MEX	5.97	3.6
RUS	UKR	3.20	2.3
IRN	AFG	1.99	9.2
PAK	AFG	1.92	2.7
HKG	CHN	1.50	7.6
RUS	UZB	1.17	3.2
DEU	TUR	1.11	2.7
DEU	RUS	1.04	2.6
ARE	IND	0.83	33.2
USA	PRI	0.83	2.7
USA	CHN	0.83	9.3
USA	PHL	0.81	10.2
SAU	IND	0.75	9.8
CIV	BFA	0.68	2.5
FRA	DZA	0.62	4.1
USA	IND	0.60	20.0
USA	RUS	0.55	3.6
USA	VNM	0.55	20.3
SAU	YEM	0.55	16.9
USA	CUB	0.51	9.3
SAU	IDN	0.51	5.5
DEU	KAZ	0.50	3.7
SGP	MYS	0.47	3.1
THA	KHM	0.46	5.4
THA	MMR	0.46	8.1
FRA	MAR	0.46	7.0
SAU	PAK	0.46	8.5
SDN	ETH	0.45	3.3
RUS	KAZ	0.45	2.0
GIN	LBR	0.44	4.9

A.3 Figures

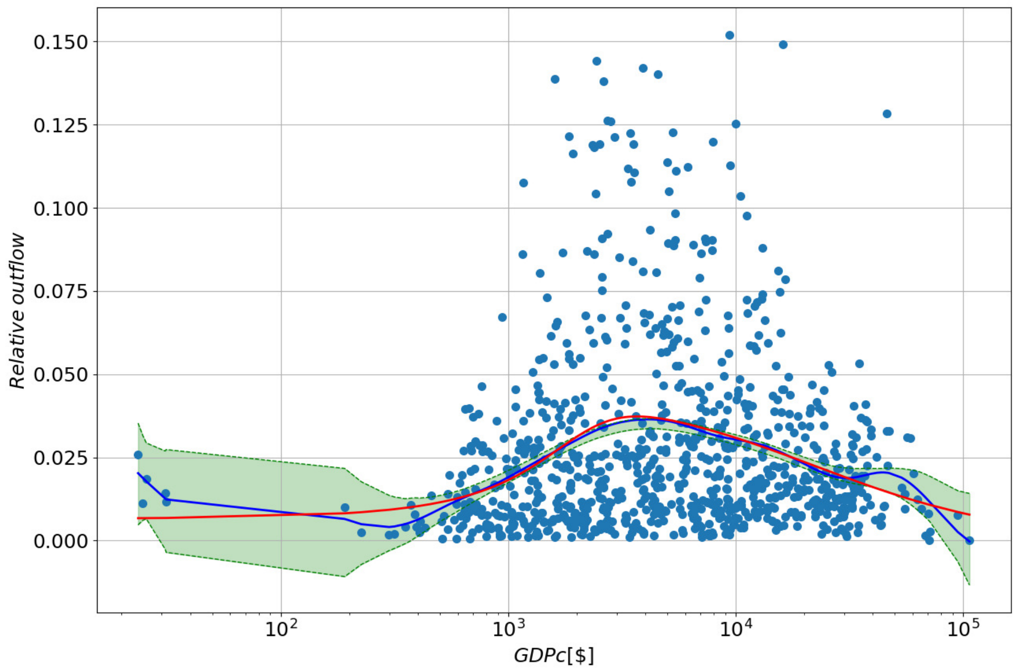


Figure A.1: Gross emigration rates against origin GDPc, as shown in Figure 2.1, but including a non-parametric, local-linear regression with a Gaussian kernel (blue line). The green coloured area shows a confidence interval of 66%, obtained through bootstrapping method. The red line shows the fit of the Equation 2.2, and is identical to the green line in Figure 2.1.

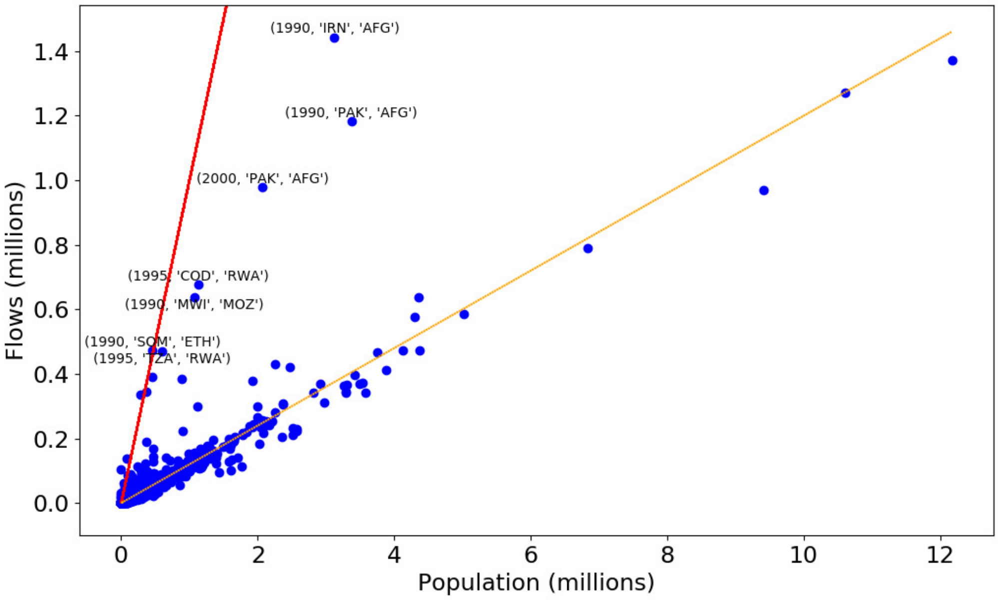


Figure A.2: Return migration flows by [103] and [104], against corresponding bilateral migrant stocks, i.e. $P_{j,i}$ in Equation 2.3. Red line is the identity line, while dashed yellow line has slope 0.12, that is the estimated value of the parameter b in Equation 2.3. The strongest outliers are labelled by the year, origin country and destination country that they represent. All of them are flows from countries experiencing civil wars, and/or regime changes in the reported period, thus plausibly explaining the high return flow rates. The flows are reproduced from the code of [104] without aggregating on the place of birth dimension. These CoB-specific flows are used here only for illustrative purposes, but are not used elsewhere in my study.

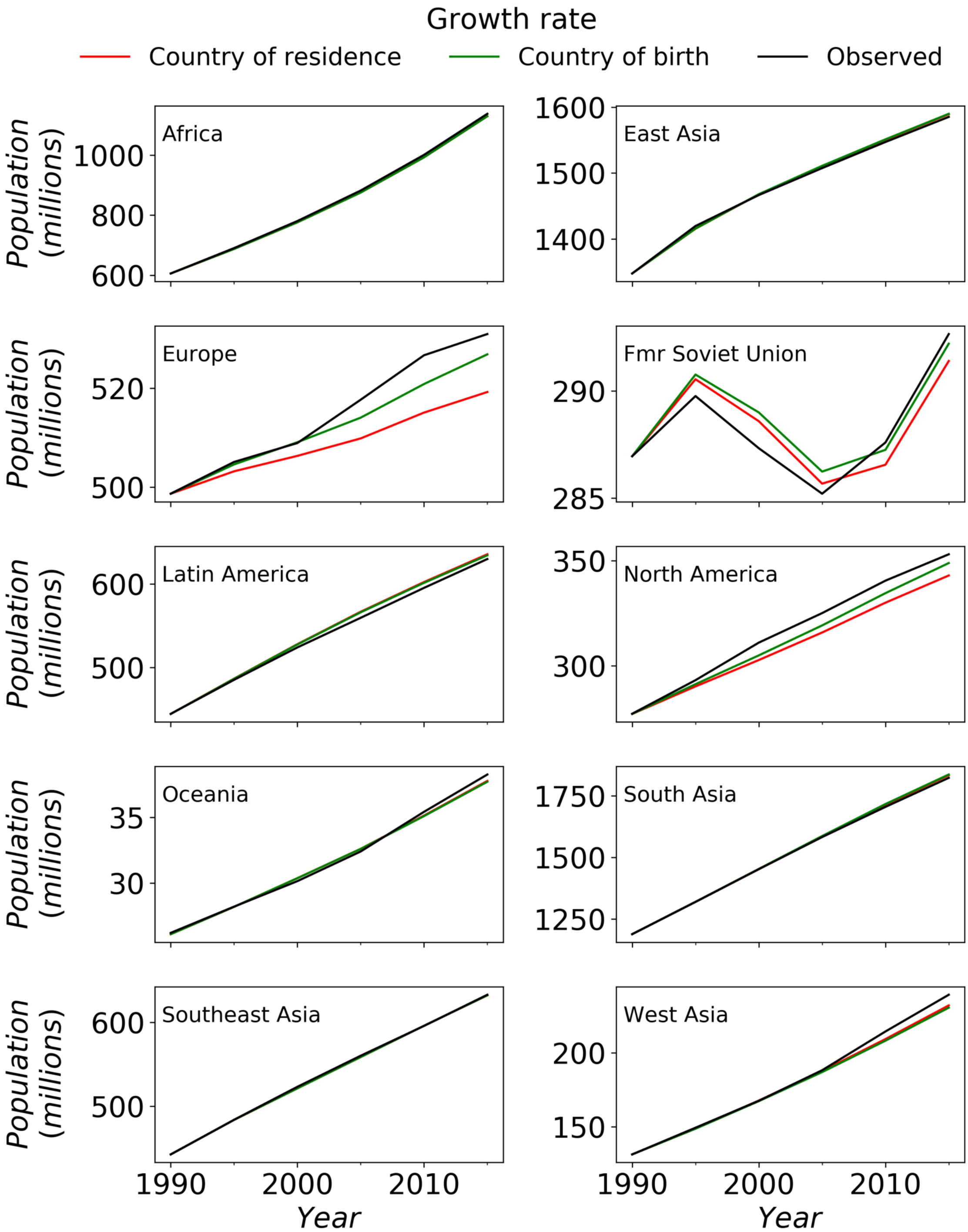


Figure A.3: Regional historical population growth. Observed (black) evolution and simulated, assuming diasporas' natural change either at the same rate as their country of birth (green) or at the same rate as their country of residence (red)

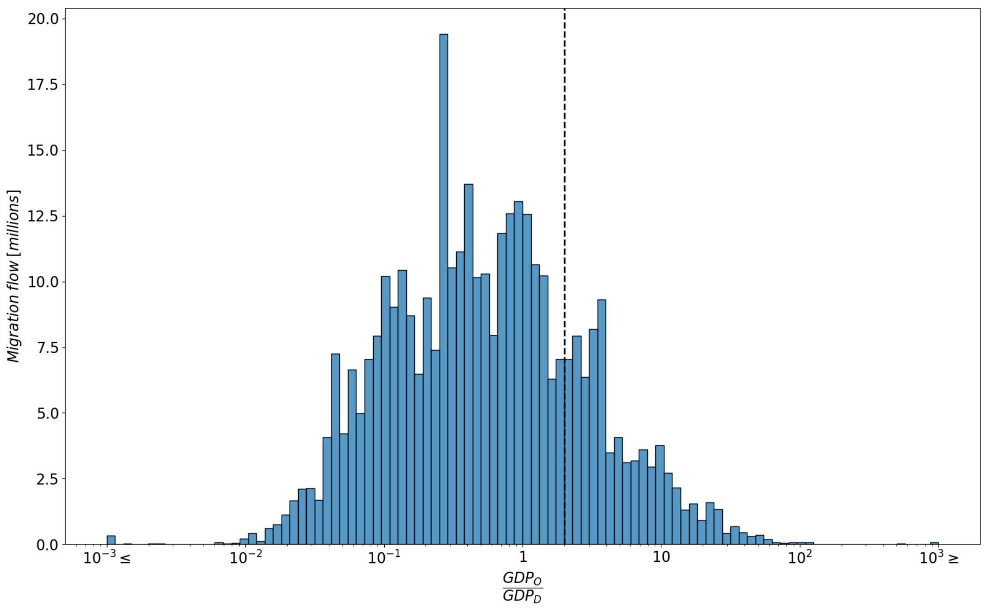


Figure A.4: Distribution of the bilateral flows from the A19 dataset against the GDPc ratio between origin and destination country of the specific flow. Dashed vertical line is set at 2; flows to the right of this line are assumed to be predominantly return flows, and are removed from the original A19 dataset for the estimation of Equation 2.2 only.

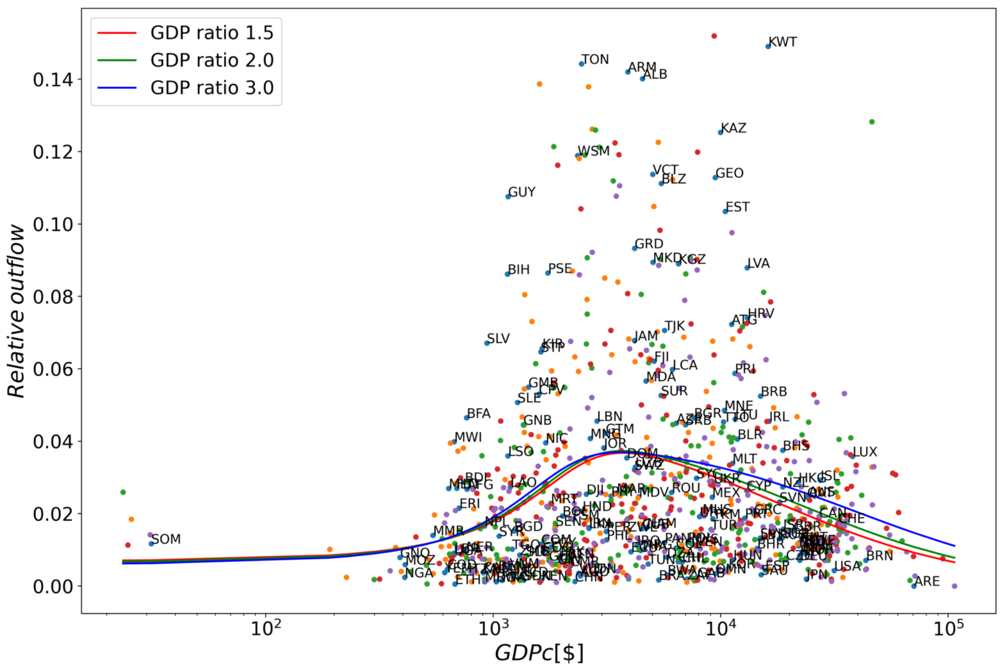


Figure A.5: Robustness analysis of the effect of the choice of GDPc ratio threshold on estimation results of Equation 2.2. Lines represent the fit of Equation 2.2 to the A19 bilateral migration flow data after removing all flows for which the ratio between origin and destination country GDPc is larger than a specific threshold. With the threshold at 3 some large flows in the sample, which are known to consist predominantly of return migrants, such as Germany to Turkey, or the United States to Puerto Rico, would not be excluded from the dataset. See also Table A.1

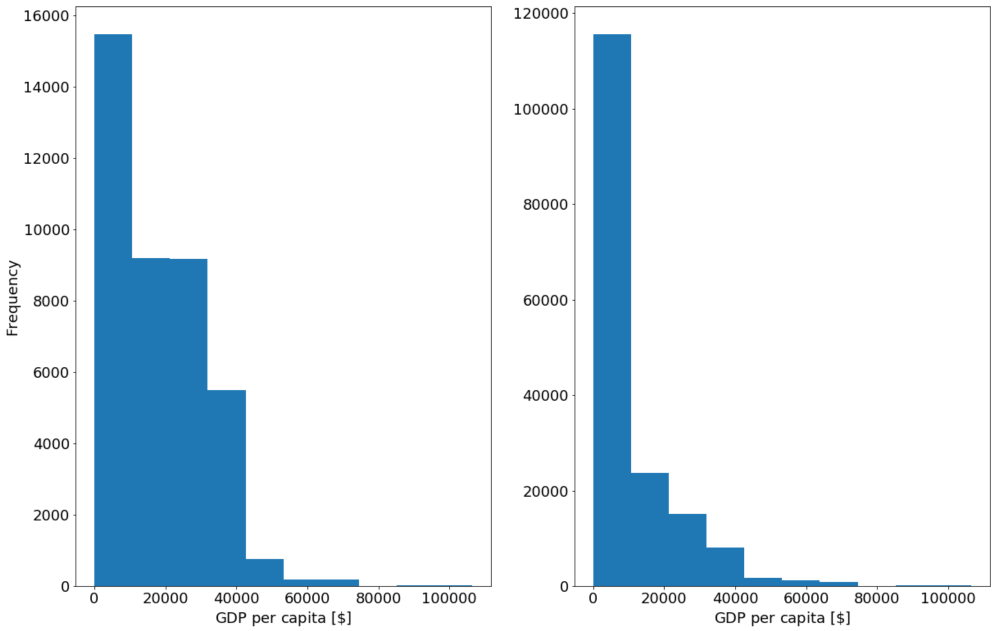


Figure A.6: Distribution of destination country GDPc in the dataset of bilateral flows derived through stock differencing (left). Same but for the A19 dataset is shown in the right panel. Note the different y-axis scale

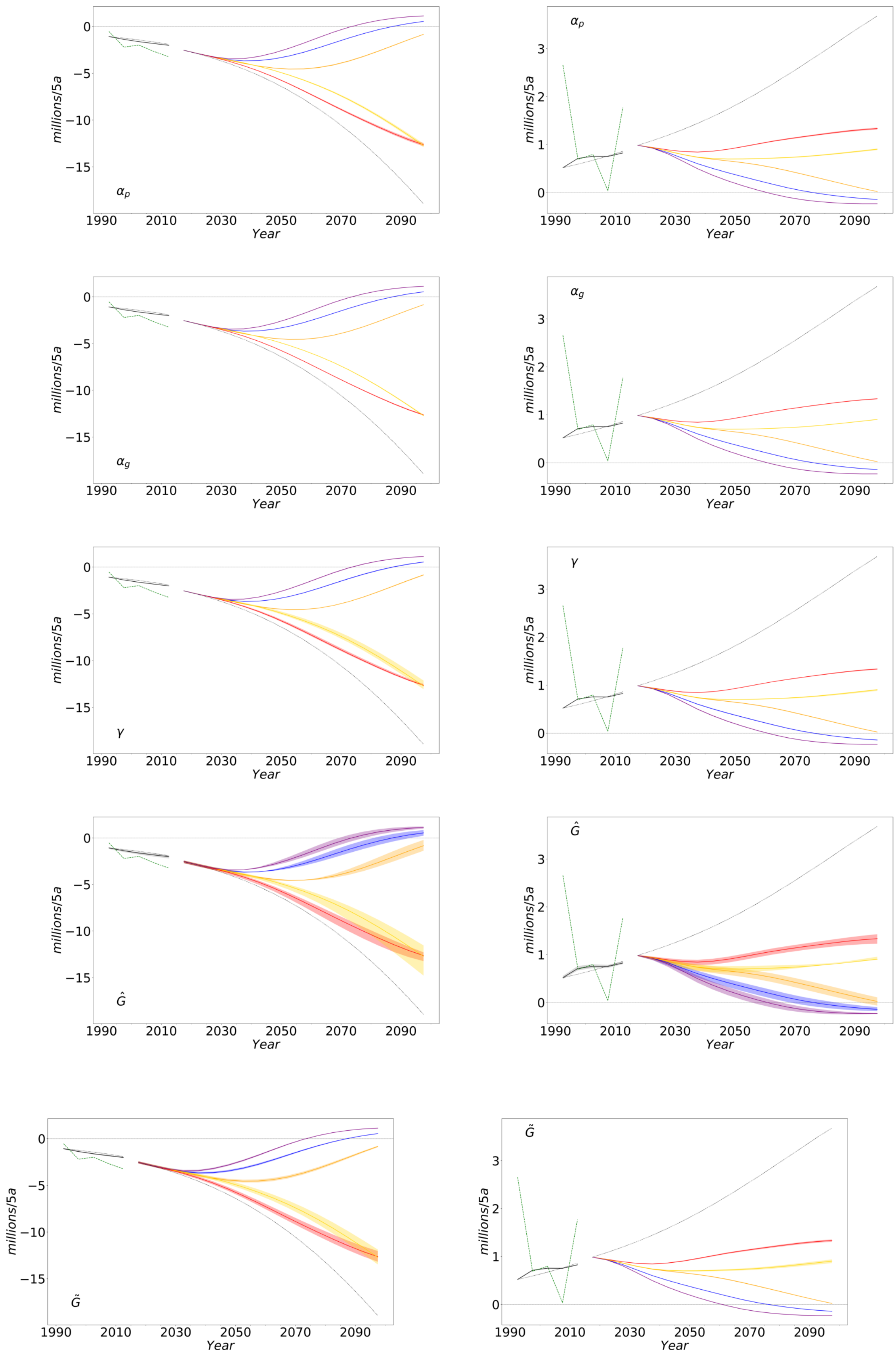


Figure A.7: Sensitivity test of the model's simulation on the parameter's uncertainty estimation. Simulation are produced by varying (shaded band) one per time the values of one parameter (reported in the figures). The test is shown for an exemplary region (Africa, left) and country (Germany, right). Solid lines are identical to those in the corresponding panels of Figures 2.4 and 2.5. Shaded band are obtained from simulations where the parameter of analysis is set to the upper and lower bound of its 66% confidence interval; while all other parameters are held at their central values.

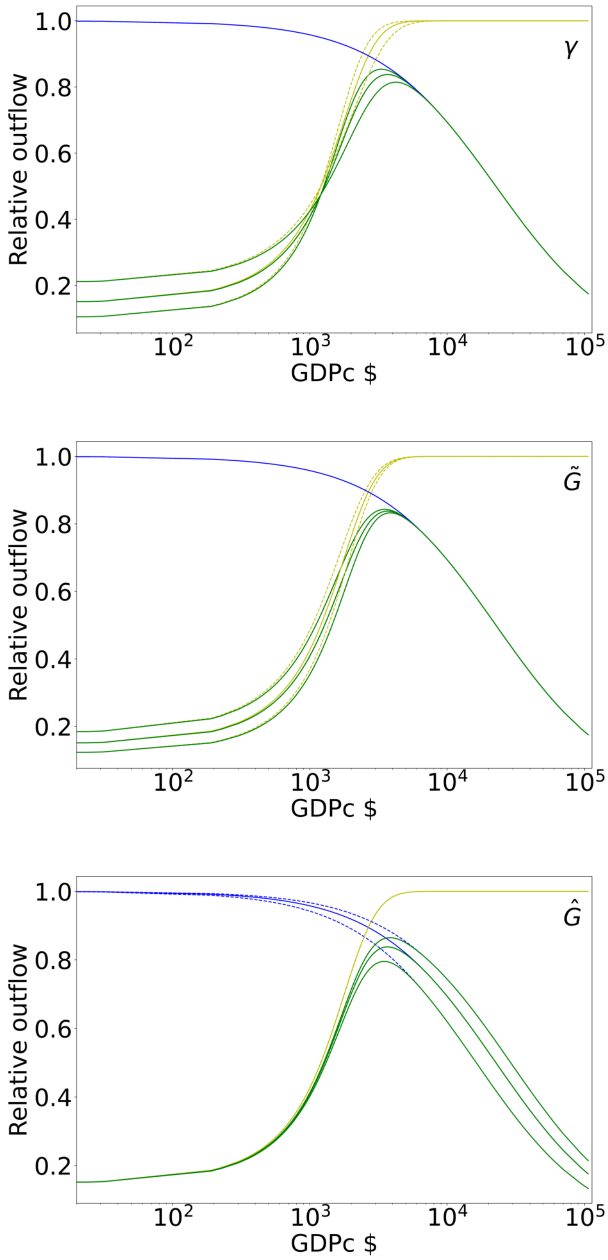


Figure A.8: Sensitivity analysis of $F(G)$ (green), F_{intent} (blue) and $F_{resource}$ (yellow) to the choice of the value of the parameters defining them. Each panel identifies the case of variation of only one of the parameters of $F(G)$, while keeping the others at their central estimated value. Variations include the upper and lower bound of the 66% confidence interval for each specific parameter.

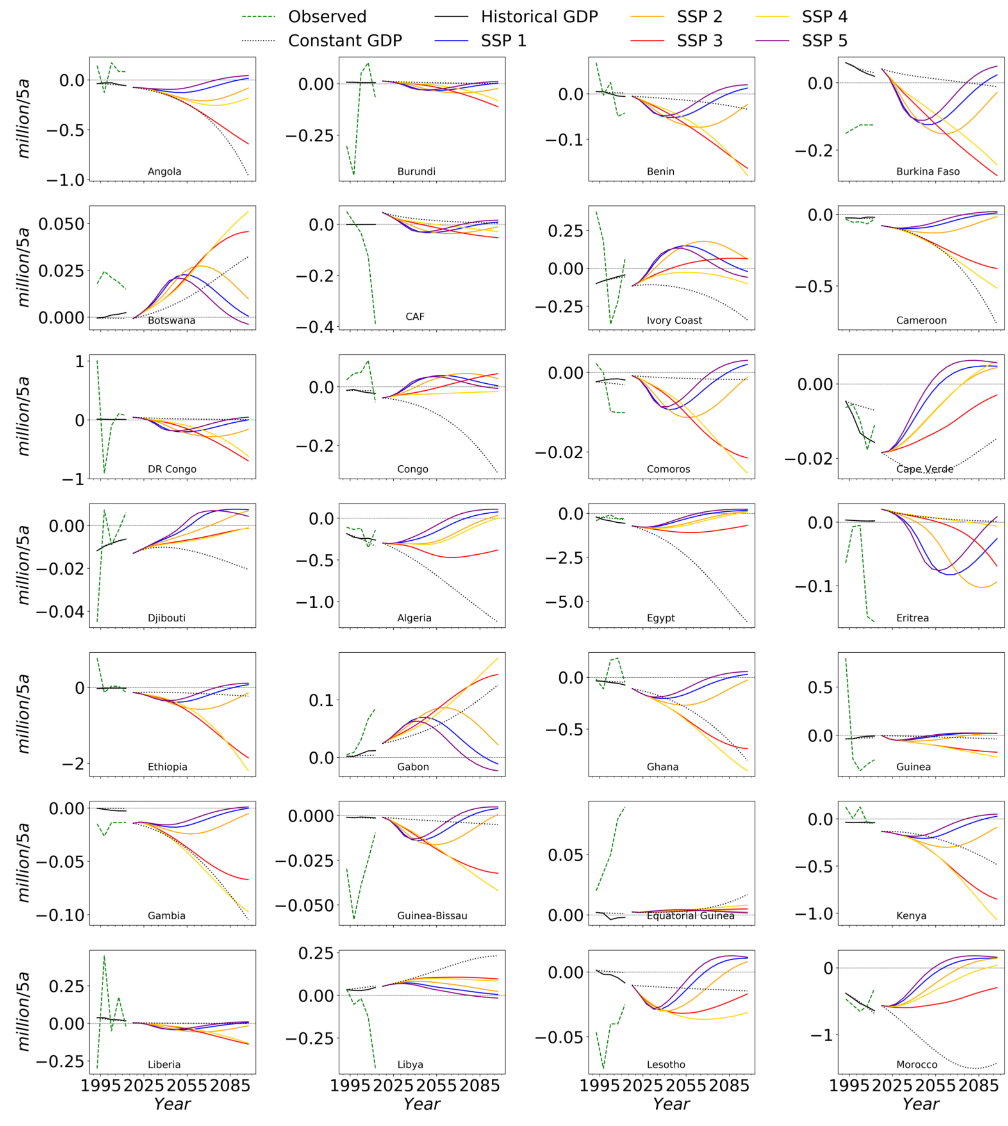


Figure A.9: As in Figure 2.5 but for other countries in Africa.

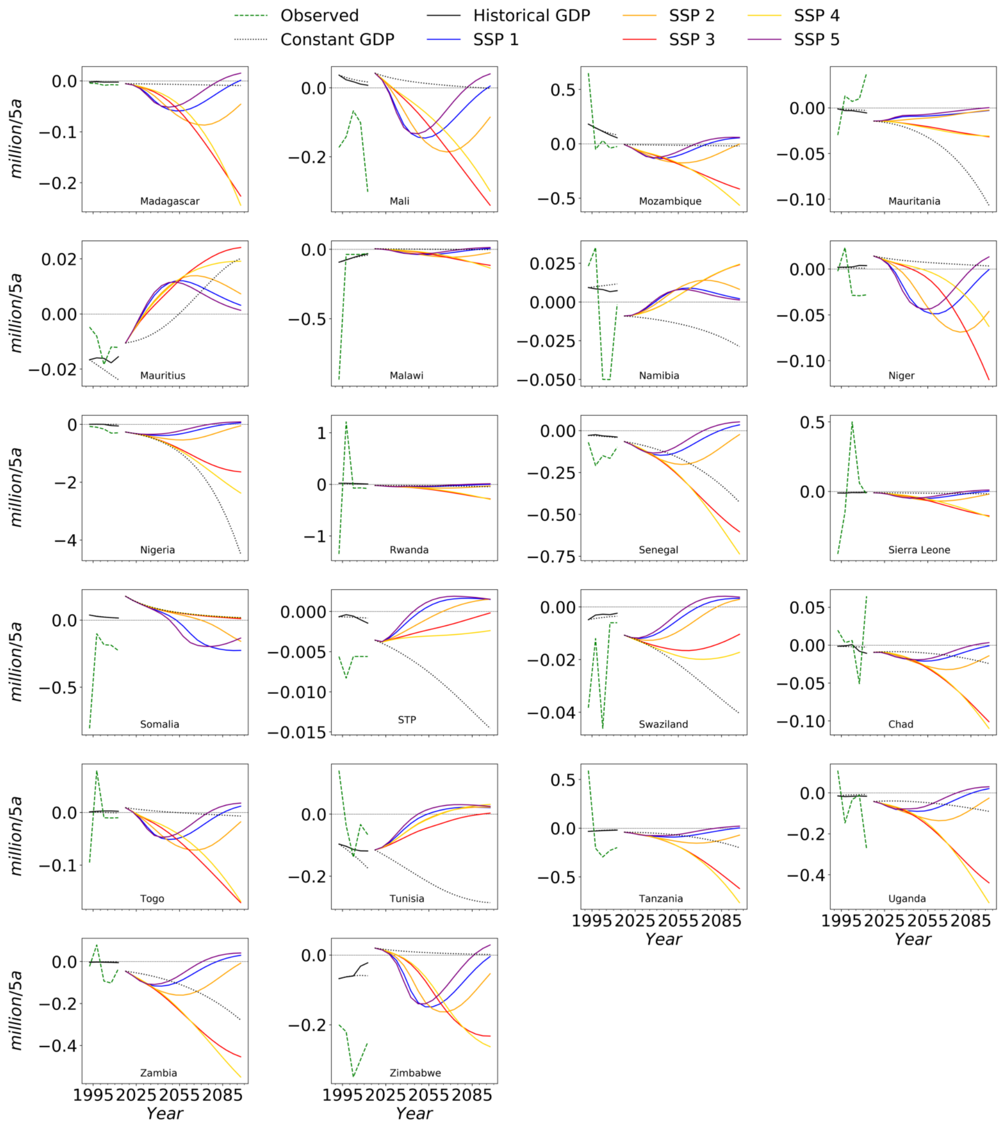


Figure A.10: As in Figure 2.5 but for other countries in Africa.

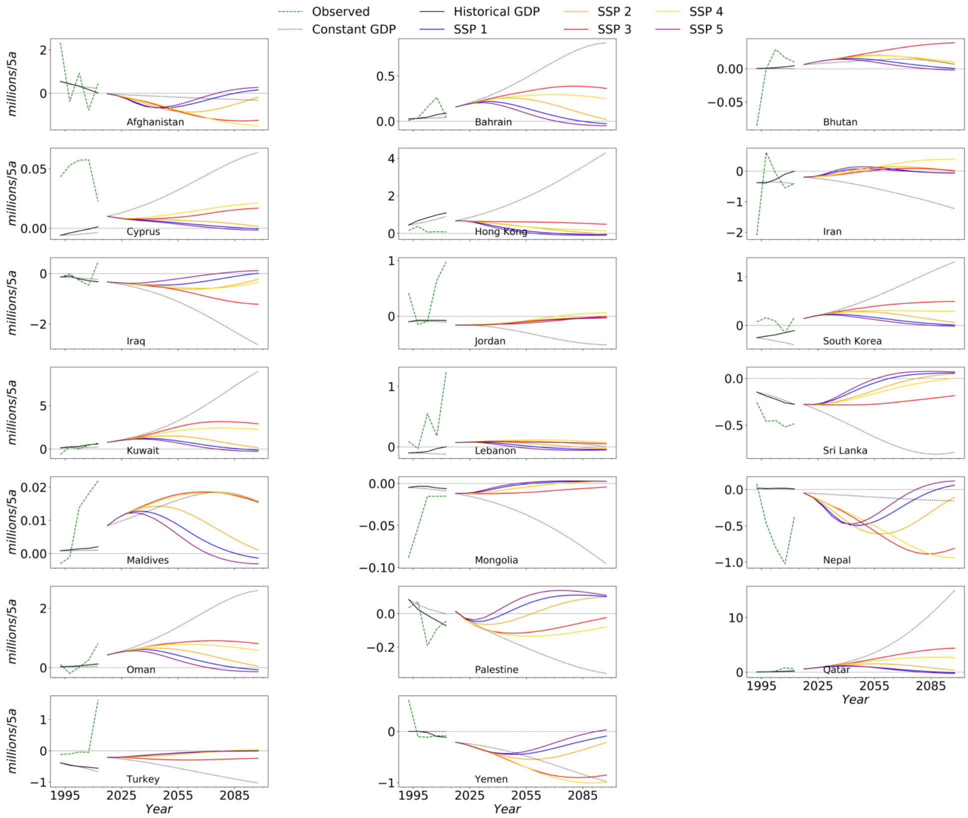


Figure A.11: As in Figure 2.5 but for other countries in Asia.

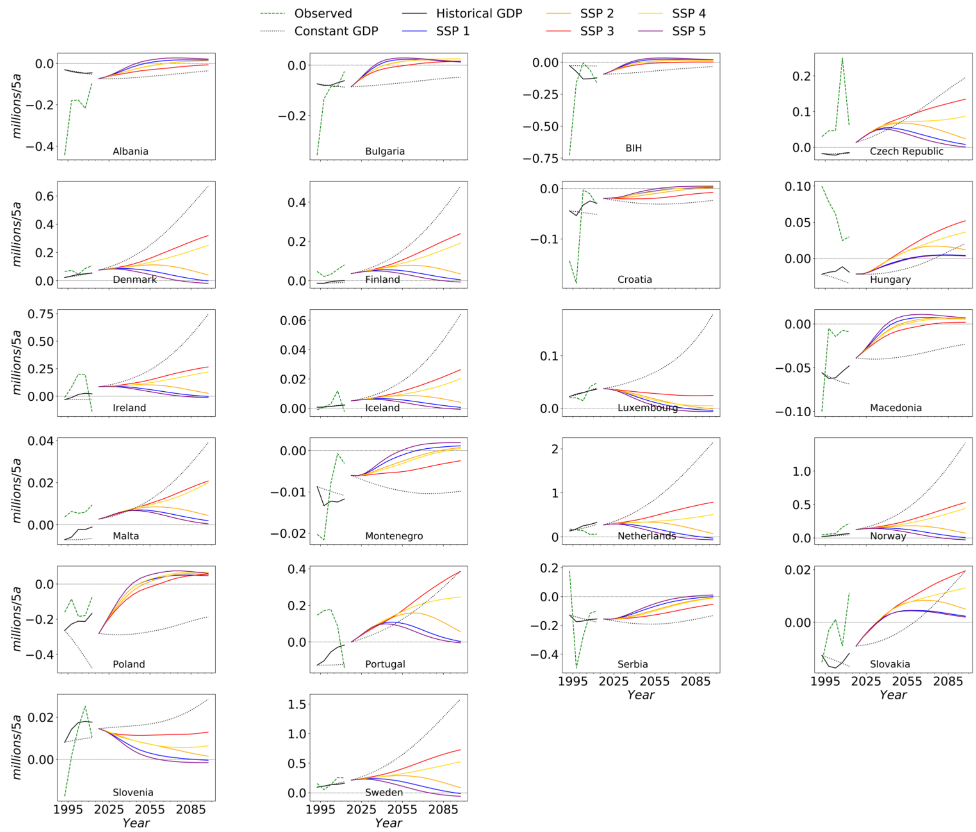


Figure A.12: As in Figure 2.5 but for other countries in Europe.

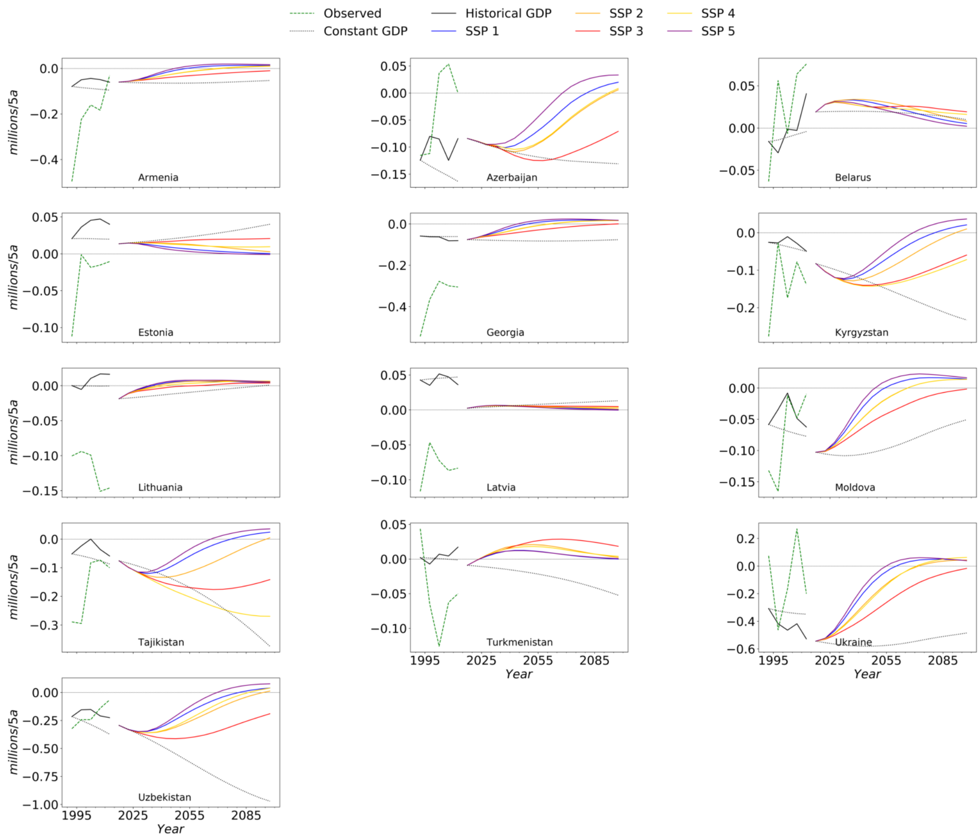


Figure A.13: As in Figure 2.5 but for other countries in Asia.

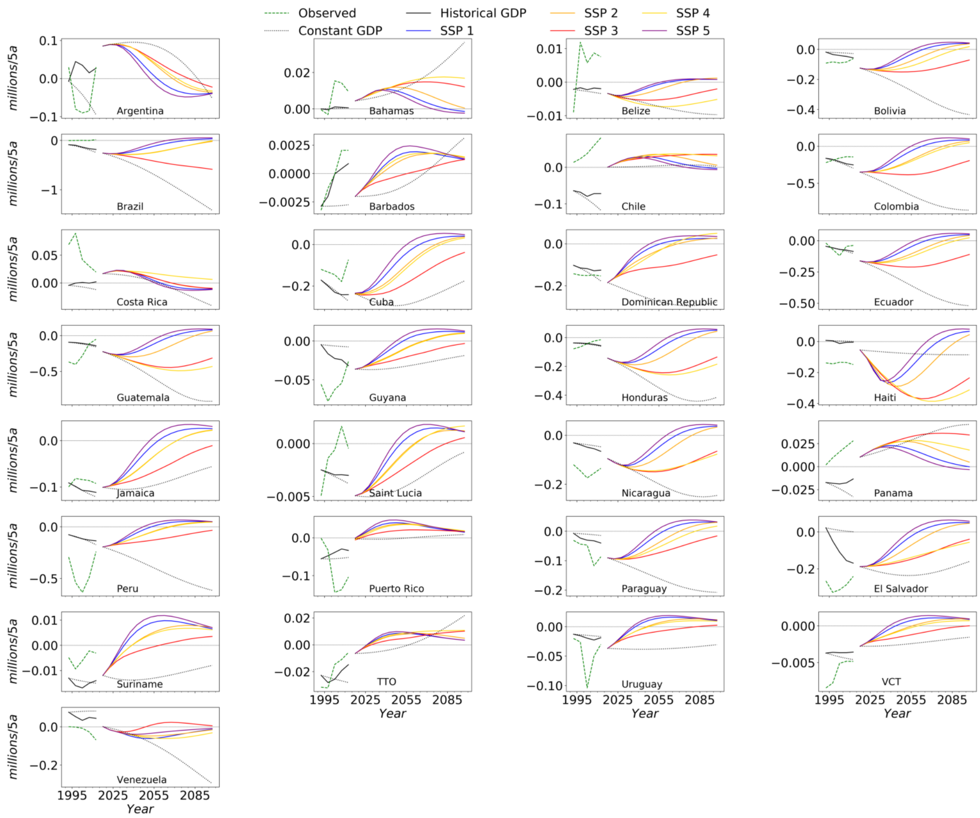


Figure A.14: As in Figure 2.5 but for other countries in Latin America.

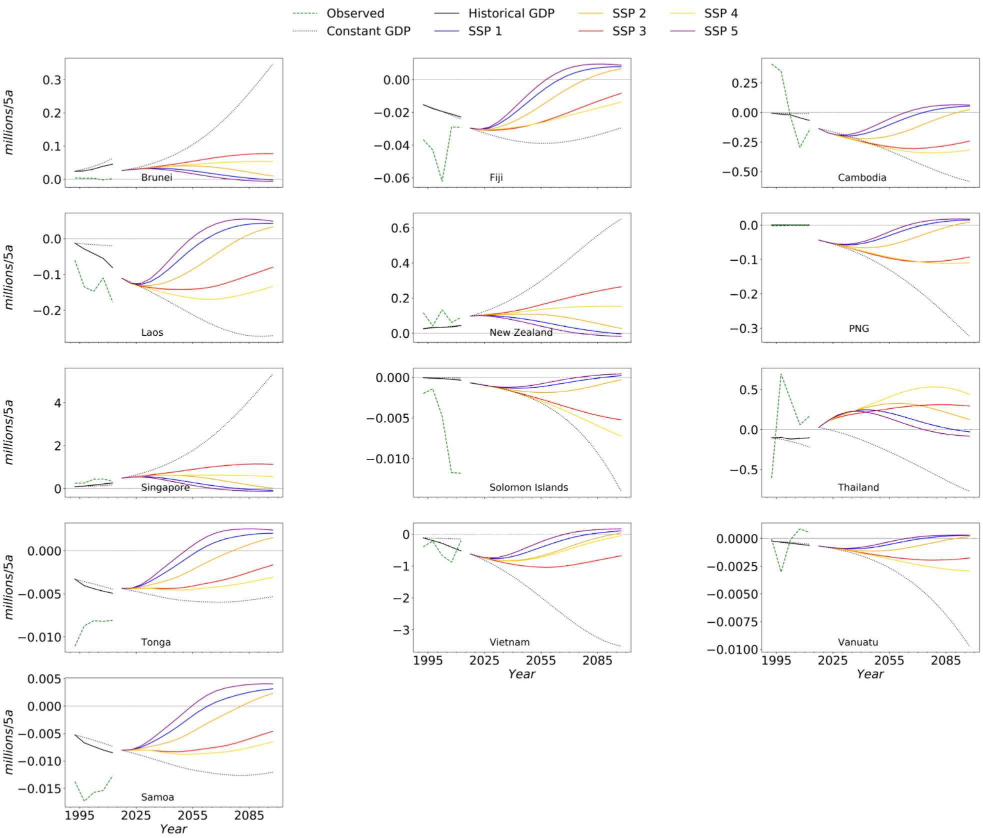


Figure A.15: As in Figure 2.5 but for other countries in Oceania.

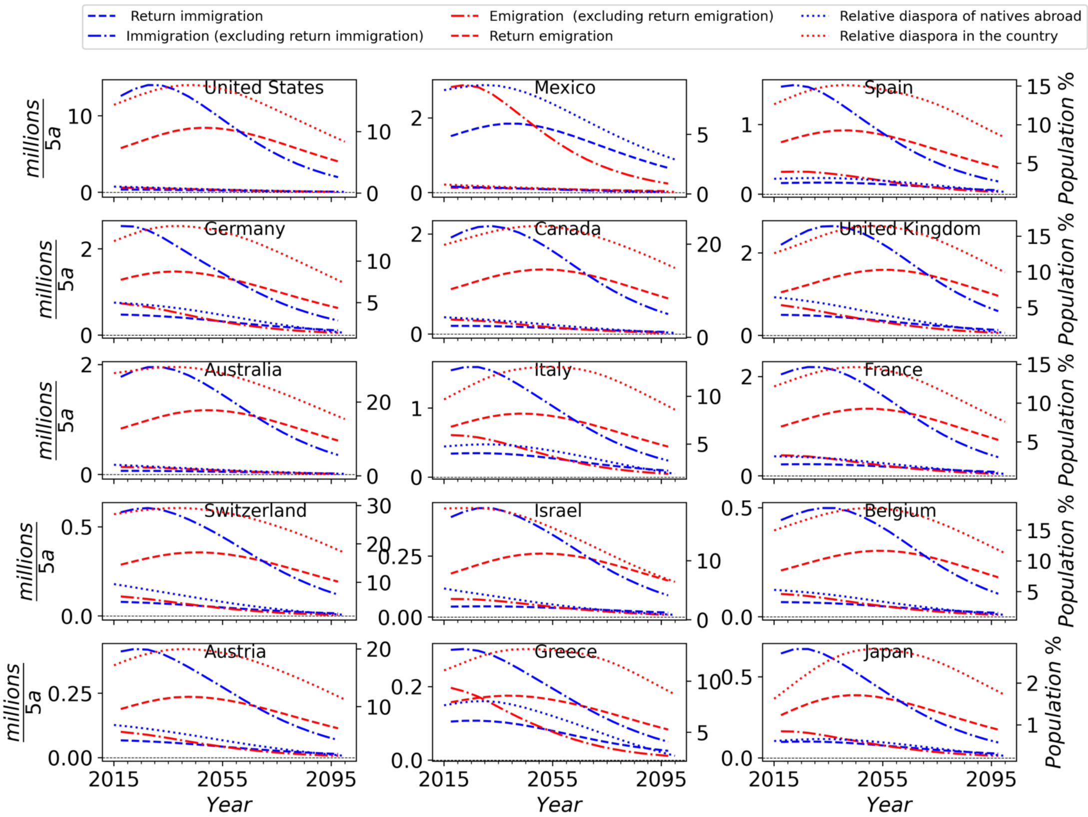


Figure A.16: Role of return migration flows in approaching zero net migration flow. Countries represented are the same shown in Figure 2.5 and under SSP 5. Dashed and dash-dotted lines (left vertical axis) show the return migration and residual component of total immigration into (blue) and total emigration out of (red) the country, respectively. Dotted lines (right vertical axis) represent the share of natives of the country living abroad (blue) and diaspora of other countries living within the country (red).

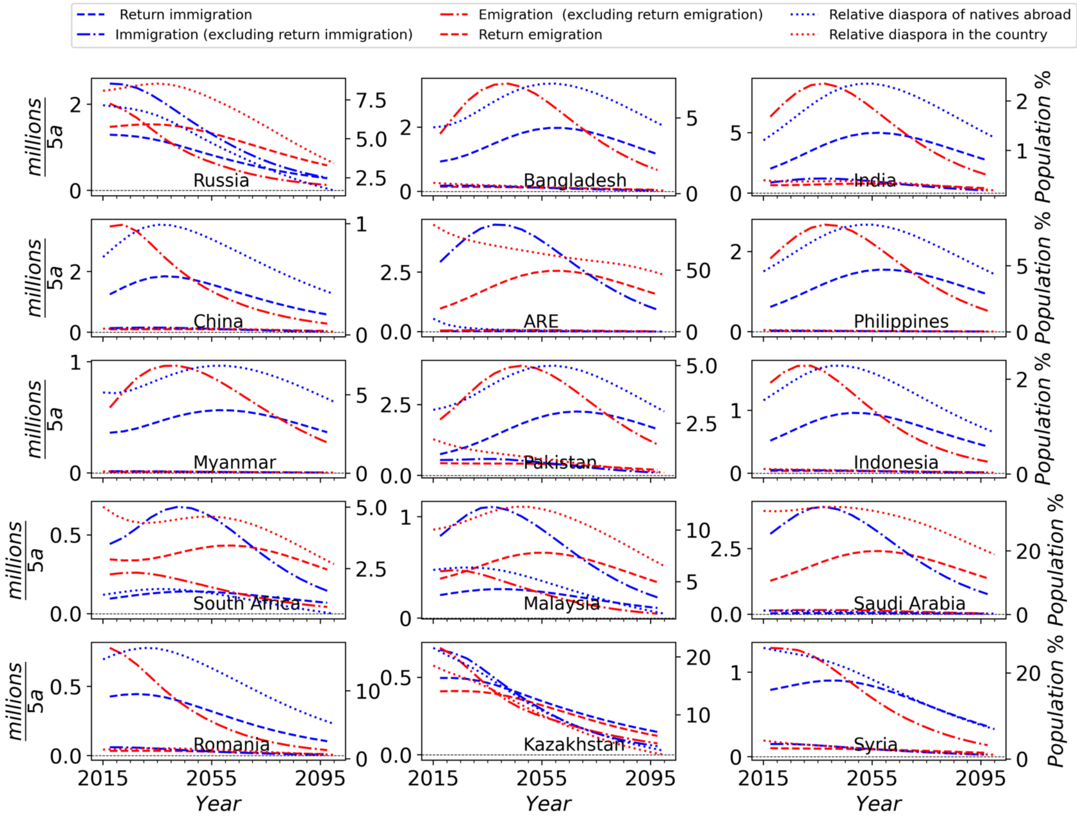


Figure A.17: As in Figure A.16 but for the countries shown in Figure 2.6.

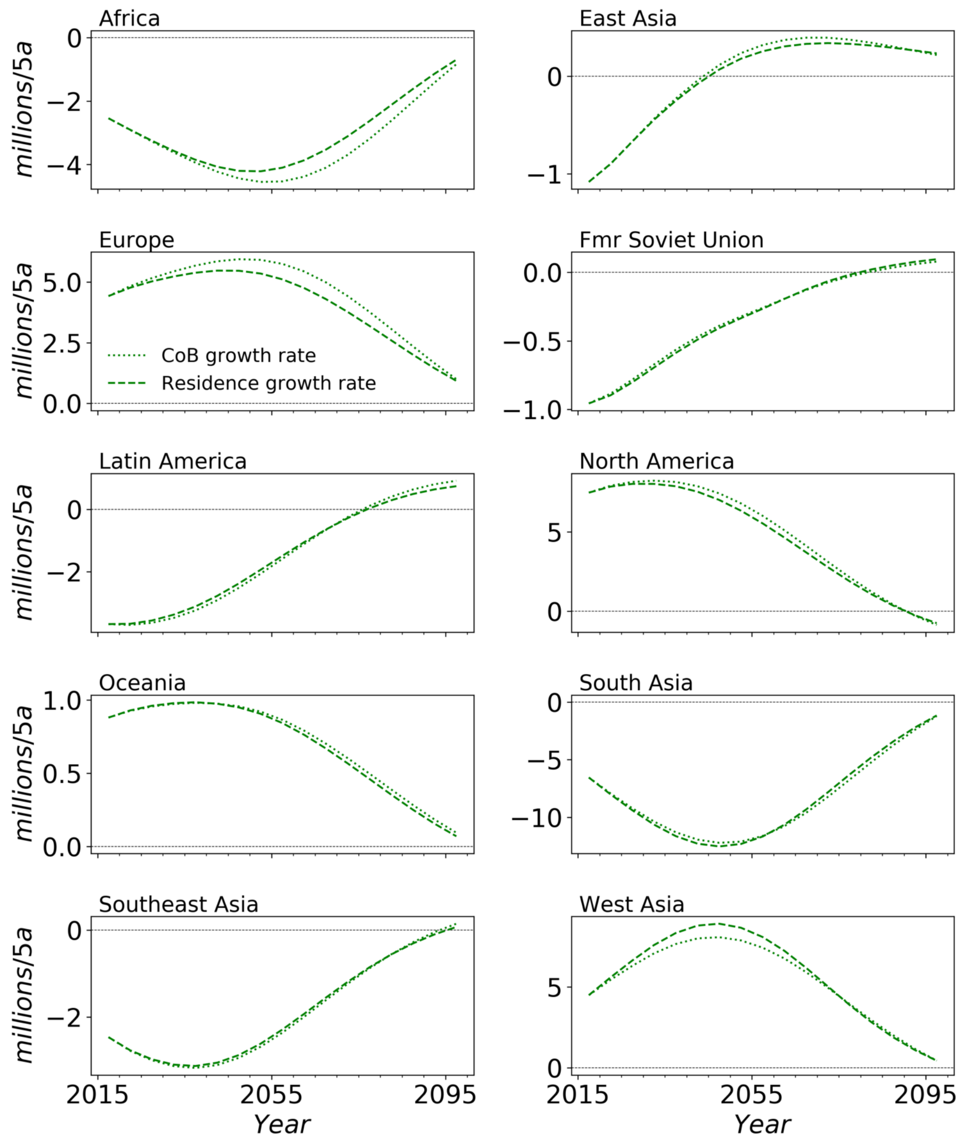


Figure A.18: Sensitivity test of projected regional net migration flows to assumptions on natural population growth rates. The case of diaspora growing at the same rate as their CoB is reported in dashed lines. When their growth rate assumes the values of their residence country, as in the main simulations, the result is reported in dotted lines.

B

Appendix B

B.1 Text

List of countries where the temperature data was missing and that of the nearest country has been used, in the format Missing Country: Substitute Country.

’ATG’:’TTO’,’BHR’: ’SAU’, ’BRB’: ’TTO’, ’GRD’:’TTO’, ’HKG’: ’CHN’, ’LCA’: ’TTO’, ’MAC’:’CHN’, ’MLT’: ’TUN’, ’SGP’: ’MYS’, ’SYC’:’TZA’,’TLS’:’IDN’, ’TON’: ’FJI’ .

List of ountries that are included in the observed migration dataset but not in my model simulation: ABW, CHI, CUW, ESH, GLP, GUF, GUM, MNE, MTQ, MYT, NCL, PRK, PYF, REU, SCG, SDN, SRB, SSD, SUD, VIR.

List of countries and years for which GDPc values were missing and have been extrapolated from the past: SOM(years 2010,2015), ERI(year 2015)

B.2 Table

Table B.1: Country-specific scaling factors estimates. The values are rounded off to three decimals digit. The countries are grouped by world region.

Country	$\tilde{a}_j$	$\tilde{b}_i$	Country	$\tilde{a}_j$	$\tilde{b}_i$
Region: Africa					
Angola	0.000	1.315	Lesotho	4.268	0.000
Burundi	0.000	3.053	Morocco	0.000	7.456
Benin	2.008	0.679	Madagascar	1.287	4.836
Burkina Faso	0.264	2.171	Mali	0.295	2.599
Botswana	2.621	0.759	Mozambique	0.682	0.642
Central African Republic	1.745	17.820	Mauritania	1.096	0.871
Ivory Coast	1.884	1.619	Mauritius	1.207	0.770
Cameroon	2.424	1.251	Malawi	0.222	4.512

DR Congo	0.531	3.877	Namibia	0.848	0.872
Congo	2.578	1.079	Niger	4.301	2.136
Comoros	0.000	2.133	Nigeria	1.934	1.055
Cape Verde	0.626	3.365	Rwanda	0.808	5.498
Djibouti	2.907	0.942	Senegal	1.266	1.455
Algeria	0.804	0.746	Sierra Leone	1.173	6.518
Egypt	1.458	0.844	Somalia	0.000	9.477
Eritrea	1.674	5.035	Sao Tome & Principe	0.000	3.402
Ethiopia	5.023	0.893	Swaziland	0.527	0.263
Gabon	1.738	3.184	Seychelles	0.932	0.966
Ghana	2.641	0.423	Chad	0.495	0.000
Guinea	2.363	5.052	Togo	2.781	1.597
Gambia	1.916	0.989	Tunisia	1.304	0.000
Guinea-Bissau	0.555	1.642	Tanzania	3.577	3.128
Equatorial Guinea	14.238	0.000	Uganda	1.319	1.706
Kenya	3.170	0.896	South Africa	4.014	0.624
Liberia	0.000	2.758	Zambia	0.480	4.239
Libya	0.688	0.902	Zimbabwe	0.956	2.725
Region: East Asia					
China	0.756	1.061	South Korea	1.384	1.228
Hong Kong	0.616	1.160	Macao	0.651	1.084
Japan	0.882	1.076	Mongolia	1.821	8.111
Region: Europe					
Albania	0.000	23.077	Hungary	1.172	0.829
Austria	1.157	1.137	Ireland	1.057	0.128
Belgium	0.780	1.066	Iceland	1.352	1.915
Bulgaria	2.191	0.000	Italy	1.327	1.053
Bosnia & Herzegovina	0.000	21.379	Luxembourg	1.037	1.167
Switzerland	1.156	1.352	Macedonia	1.174	0.000
Czech Republic	1.005	1.034	Malta	2.168	1.013
Germany	0.972	1.161	Netherlands	0.737	1.105
Denmark	1.030	1.106	Norway	1.203	0.967
Spain	1.141	1.190	Poland	0.482	1.080
Finland	1.071	0.000	Portugal	0.575	1.025
France	0.795	1.124	Romania	1.390	1.152
United Kingdom	1.233	0.947	Slovakia	0.988	1.463
Greece	0.000	1.023	Slovenia	0.850	0.899
Croatia	0.310	0.794	Sweden	1.011	1.164
Region: Fmr Soviet Union					
Armenia	0.768	1.839	Latvia	0.445	1.711
Azerbaijan	0.265	0.000	Moldova	0.645	1.094

Belarus	0.634	0.394	Russia	1.062	0.788
Estonia	0.461	1.408	Tajikistan	0.611	2.695
Georgia	0.000	14.845	Turkmenistan	0.526	1.837
Kazakhstan	0.593	1.668	Ukraine	0.710	0.453
Kyrgyzstan	0.661	2.190	Uzbekistan	0.741	0.830
Lithuania	0.432	2.576			
Region: Latin America					
Argentina	0.848	1.135	Haiti	0.000	44.716
Bahamas	1.643	1.011	Jamaica	0.000	0.000
Belize	1.188	0.825	Kiribati	0.000	18.332
Bolivia	0.393	0.414	Saint Lucia	1.291	0.000
Brazil	1.006	0.846	Mexico	0.000	0.000
Barbados	0.521	0.148	Nicaragua	0.000	8.118
Chile	3.144	1.132	Panama	1.268	0.999
Colombia	0.000	0.338	Peru	4.553	35.075
Costa Rica	1.432	0.965	Puerto Rico	0.000	2.422
Cuba	0.000	3.857	Paraguay	0.531	1.757
Dominican Republic	1.739	1.003	El Salvador	0.000	25.262
Ecuador	1.309	0.955	Suriname	0.000	0.106
Grenada	2.916	3.509	Trinidad & Tobago	0.173	0.000
Guatemala	0.000	1.153	Uruguay	0.512	2.788
Guyana	0.000	11.733	Saint Vincent and Grenadine	0.927	4.387
Honduras	0.000	0.609	Venezuela	1.078	4.798
Region: North America					
Canada	1.152	1.014	United States of America	1.062	1.034
Region: Oceania					
Antigua and Barbadua	1.399	1.081	Papua New Guinea	1.492	2.212
Australia	1.091	1.074	Solomon Islands	0.641	10.399
Fiji	0.000	7.908	Tonga	0.000	2.630
Micronesia	0.000	74.279	Vanuatu	0.667	2.860
New Zealand	1.111	1.272	Samoa	0.000	9.344
Region: South Asia					
Afghanistan	0.000	3.034	Sri Lanka	0.197	2.246
Bangladesh	2.180	2.826	Maldives	3.248	0.697
Bhutan	0.622	0.950	Nepal	0.974	4.400
India	1.408	0.866	Pakistan	1.156	1.659
Iran	0.896	1.484			
Region: Southeast Asia					
Brunei	0.554	1.178	Philippines	0.259	3.239
Indonesia	0.377	0.986	Singapore	1.057	1.015

Cambodia	2.346	0.024	Thailand	1.618	0.918
Laos	0.229	0.000	Timor-Leste	0.000	34.714
Myanmar	0.386	3.563	Vietnam	1.695	6.966
Malaysia	1.267	0.923			
Region: West Asia					
United Arab Emirates	0.864	1.083	Oman	1.405	1.076
Bahrain	1.096	1.011	Palestine	0.000	0.930
Cyprus	1.737	0.000	Qatar	0.893	1.049
Iraq	0.808	0.353	Saudi Arabia	0.912	1.117
Israel	0.855	1.286	Syria	1.044	3.884
Jordan	1.323	0.649	Turkey	2.654	0.682
Kuwait	0.866	1.154	Yemen	6.035	1.157
Lebanon	0.784	0.619			

B.3 Figures

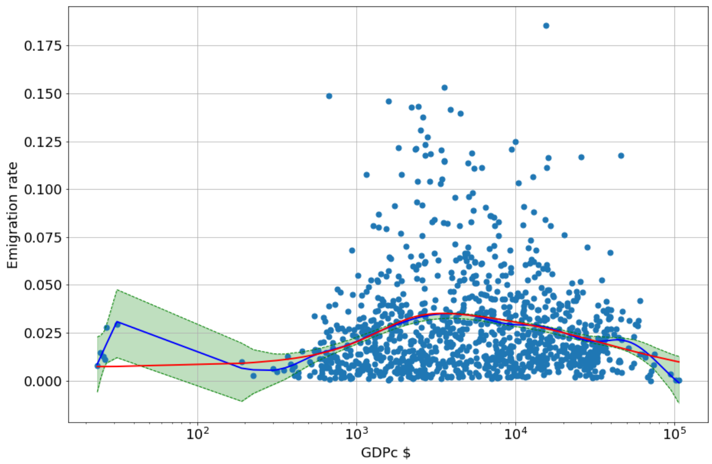
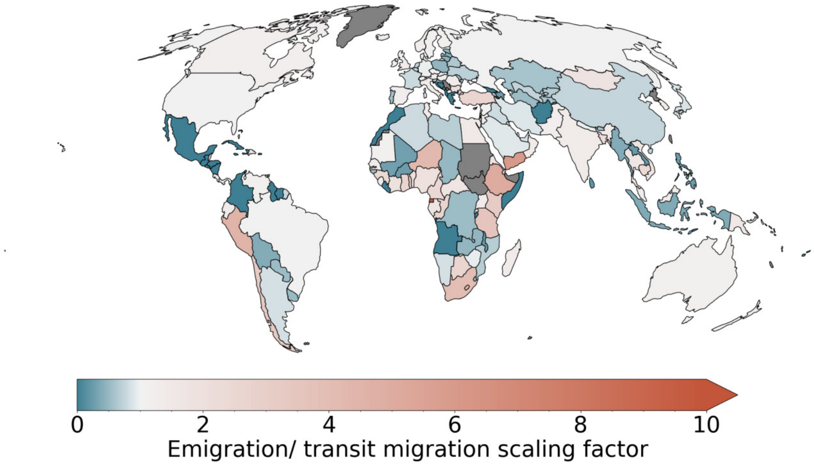
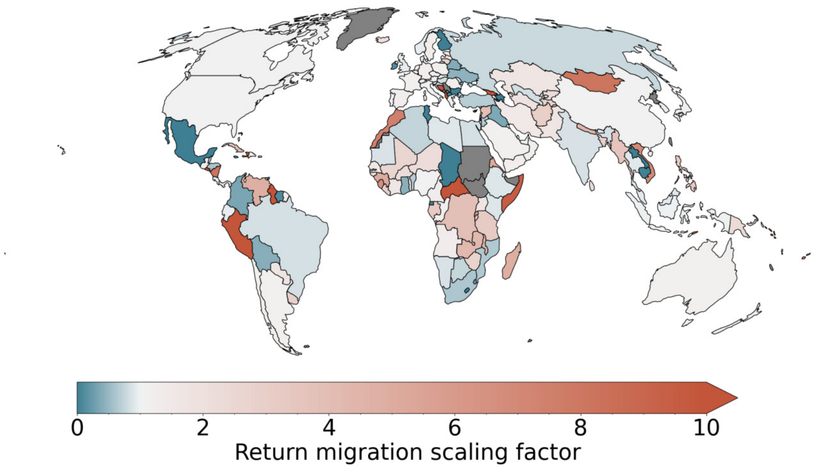


Figure B.1: Estimated emigration-origin GDPc relation as described in the Methods section. Each point represents the total emigration rate and GDPc of a country in one specific year. The red curve represents the result from the nonlinear least squares regression while the blue curve is the result of a non-parametric regression where a local-linear regression with a Gaussian kernel method has been used. The green area shows the confidence interval of 66% using a bootstrapping method on the non-parametric regression.

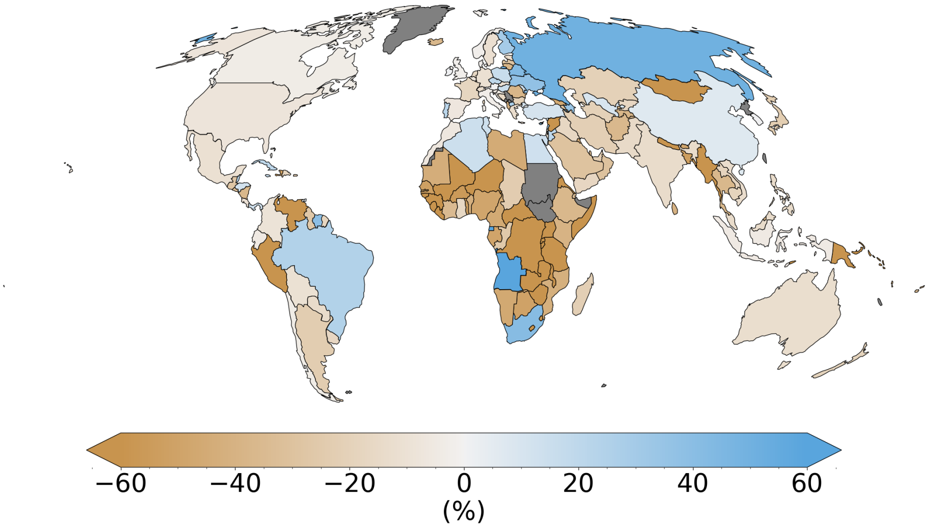


(a) Destination country-specific scaling factor.

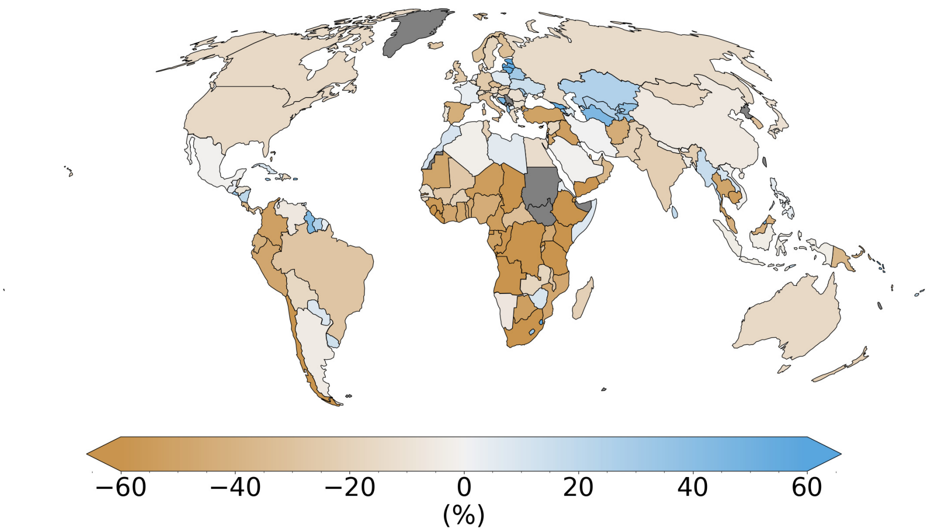


(b) Origin country-specific scaling factor

Figure B.2: Country-specific scaling factors, estimated from the bilateral migration flows. Panel (a) shows the values for the $\tilde{a}_j$ factors used for the emigration from CoB and transit migration. Panel (b) shows the estimates for the country-specific scaling factors $\tilde{b}_i$ used for the return migration.



(a) Emigration



(b) Immigration

Figure B.3: As in Figure 3.2e and Figure 3.2f but for the model without country specific scaling factors.

C

Appendix C

C.1 Text

When temperature data was missing I have used the temperature of the nearest country. All these cases appear for small countries. The following list reports these countries and their substitute, using the 3digits ISO code, in the format "country with missing data: substitute country": BHR: SAU, BRB: TTO, HKG: CHN, LCA: TTO, MAC:CHN, MLT: TUN, PSE: ISR, SGP: MYS, TLS: IDN, TON: FJI, VUT: FJI.

List of countries and years for which GDPc values were missing and have been extrapolated from the past: SOM(years 2010,2015), ERI(year 2015).

C.2 Tables

Table C.1: GCM models used as the source for the climate projections. The reported year defines the 30-year period of interest, i.e. when the 3 global warming is reached, as $[t-14, t+15]$, where t is the reported year.

Climate model	SSP3-7.0	SSP5-8.5
IPSL-CM6A-LR	2060	2055
EC-Earth3	2055	2050
MPI-ESM1-2-HR	2080	2070
UKESM1-0-LL	2045	2045
CNRM-CM6-1	2065	2060
GFDL-ESM4	2070	2065
MRI-ESM2-0	2065	2060
CanESM5	2050	2045
CNRM-ESM2-1	2070	2060
MIROC6	2075	2065

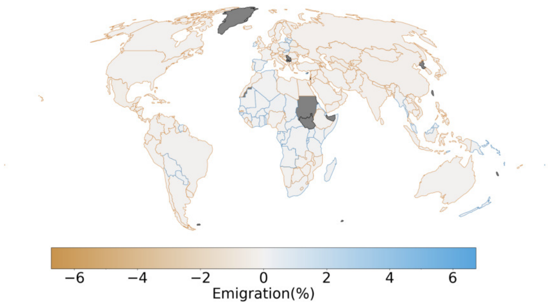
Table C.2: Estimates of the country-specific scaling factors. The values are rounded off to three decimals digit and countries are grouped by regions.

Country	$\tilde{a}_j$	$\tilde{b}_i$	Country	$\tilde{a}_j$	$\tilde{b}_i$
Region: Africa					
AGO	0.000	1.315	LSO	4.268	0.000
BDI	0.000	3.053	MAR	0.000	7.456
BEN	2.008	0.679	MDG	1.287	4.836
BFA	0.264	2.171	MLI	0.295	2.599
BWA	2.621	0.759	MOZ	0.682	0.642
CAF	1.745	17.820	MRT	1.096	0.871
CIV	1.884	1.619	MUS	1.207	0.770
CMR	2.424	1.251	MWI	0.222	4.512
COD	0.531	3.877	NAM	0.848	0.872
COG	2.578	1.079	NER	4.301	2.136
COM	0.000	2.133	NGA	1.934	1.055
CPV	0.626	3.365	RWA	0.808	5.498
DJI	2.907	0.942	SEN	1.266	1.455
DZA	0.804	0.746	SLE	1.173	6.518
EGY	1.458	0.844	SOM	0.000	9.477
ERI	1.674	5.035	STP	0.000	3.402
ETH	5.023	0.893	SWZ	0.527	0.263
GAB	1.738	3.184	TCD	0.495	0.000
GHA	2.641	0.423	TGO	2.781	1.597
GIN	2.363	5.052	TUN	1.304	0.000
GMB	1.916	0.989	TZA	3.577	3.128
GNB	0.555	1.642	UGA	1.319	1.706
GNQ	14.238	0.000	ZAF	4.014	0.624
KEN	3.170	0.896	ZMB	0.480	4.239
LBR	0.000	2.758	ZWE	0.956	2.725
LBY	0.688	0.902			
Region: East Asia					
CHN	0.755	1.061	KOR	1.384	1.228
HKG	0.616	1.160	MAC	0.651	1.084
JPN	0.881	1.076	MNG	1.821	8.111
Region: Europe					
ALB	0.000	23.077	HUN	1.172	0.829
AUT	1.157	1.137	IRL	1.057	0.128
BEL	0.780	1.067	ISL	1.352	1.915
BGR	2.191	0.000	ITA	1.327	1.053
BIH	0.000	21.379	LUX	1.037	1.167
CHE	1.157	1.352	MKD	1.174	0.000

CZE	1.005	1.034	MLT	2.168	1.013
DEU	0.972	1.161	NLD	0.737	1.105
DNK	1.030	1.106	NOR	1.203	0.967
ESP	1.141	1.190	POL	0.482	1.080
FIN	1.071	0.000	PRT	0.575	1.025
FRA	0.795	1.124	ROU	1.390	1.152
GBR	1.233	0.947	SVK	0.988	1.463
GRC	0.000	1.023	SVN	0.850	0.899
HRV	0.310	0.794	SWE	1.011	1.164
Region: Fmr Soviet Union					
ARM	0.768	1.839	LVA	0.445	1.711
AZE	0.265	0.000	MDA	0.645	1.094
BLR	0.634	0.394	RUS	1.062	0.788
EST	0.461	1.409	TJK	0.611	2.695
GEO	0.000	14.845	TKM	0.526	1.837
KAZ	0.593	1.667	UKR	0.710	0.453
KGZ	0.661	2.190	UZB	0.741	0.830
LTU	0.432	2.576			
Region: Latin America					
ARG	0.848	1.135	HTI	0.000	44.716
BHS	1.643	1.011	JAM	0.000	0.000
BLZ	1.188	0.825	LCA	1.291	0.000
BOL	0.393	0.414	MEX	0.000	0.000
BRA	1.006	0.846	NIC	0.000	8.118
BRB	0.521	0.148	PAN	1.268	0.999
CHL	3.144	1.132	PER	4.553	35.075
COL	0.000	0.338	PRI	0.000	2.422
CRI	1.432	0.965	PRY	0.531	1.757
CUB	0.000	3.857	SLV	0.000	25.262
DOM	1.739	1.003	SUR	0.000	0.106
ECU	1.309	0.955	TTO	0.173	0.000
GTM	0.000	1.153	URY	0.512	2.788
GUY	0.000	11.733	VCT	0.927	4.387
HND	0.000	0.609	VEN	1.078	4.798
Region: North America					
CAN	1.152	1.014	USA	1.062	1.034
Region: Oceania					
AUS	1.091	1.074	SLB	0.641	10.399
FJI	0.000	7.908	TON	0.000	2.630
NZL	1.111	1.272	VUT	0.667	2.860

PNG	1.492	2.212	WSM	0.000	9.344
Region: South Asia					
AFG	0.000	3.034	LKA	0.197	2.245
BGD	2.180	2.826	MDV	3.248	0.697
BTN	0.622	0.950	NPL	0.974	4.400
IND	1.408	0.867	PAK	1.156	1.659
IRN	0.896	1.484			
Region: Southeast Asia					
BRN	0.554	1.178	PHL	0.259	3.239
IDN	0.377	0.986	SGP	1.057	1.015
KHM	2.346	0.024	THA	1.618	0.918
LAO	0.229	0.000	TLS	0.000	34.714
MMR	0.386	3.563	VNM	1.695	6.966
MYS	1.267	0.923			
Region: West Asia					
ARE	0.864	1.083	OMN	1.405	1.076
BHR	1.096	1.011	PSE	0.000	0.930
CYP	1.737	0.000	QAT	0.893	1.049
IRQ	0.808	0.353	SAU	0.912	1.117
ISR	0.855	1.286	SYR	1.044	3.884
JOR	1.323	0.649	TUR	2.654	0.682
KWT	0.866	1.154	YEM	6.035	1.157
LBN	0.784	0.619			

C.3 Figures



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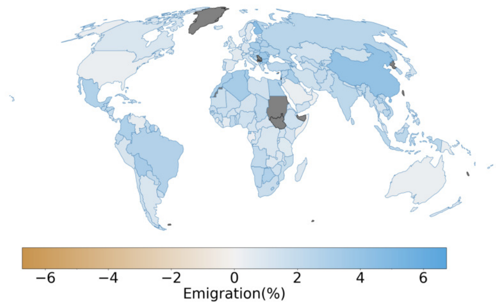

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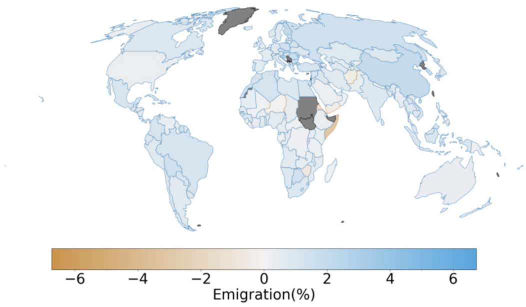

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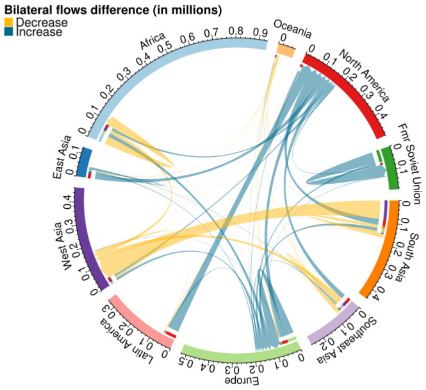
Figure C.1: As in Figure 4.4 but for the long-term climate change impact.



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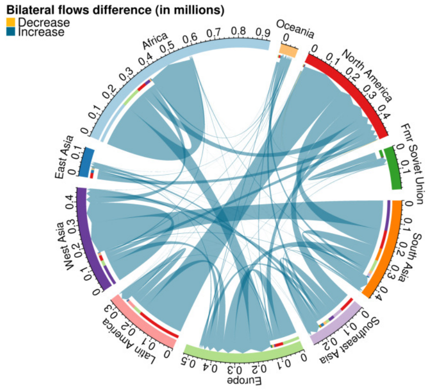

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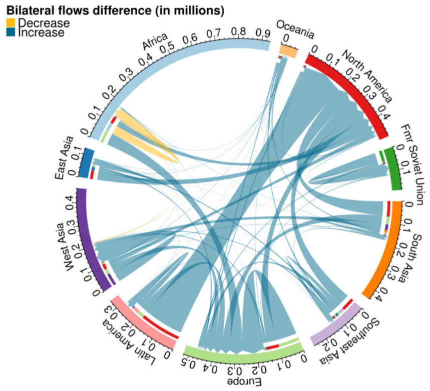

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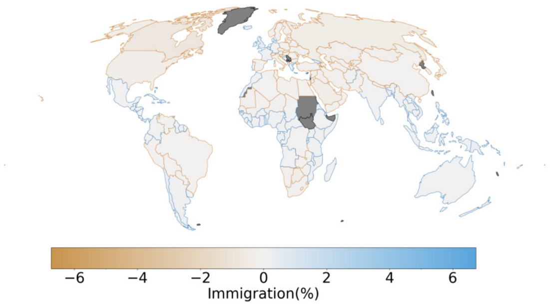
Figure C.2: As in Figure 4.6 but for the difference in absolute terms.



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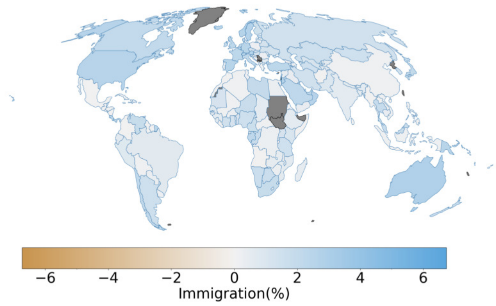

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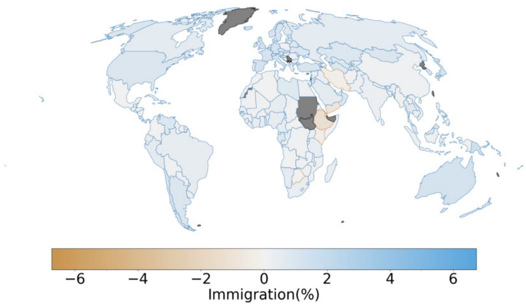

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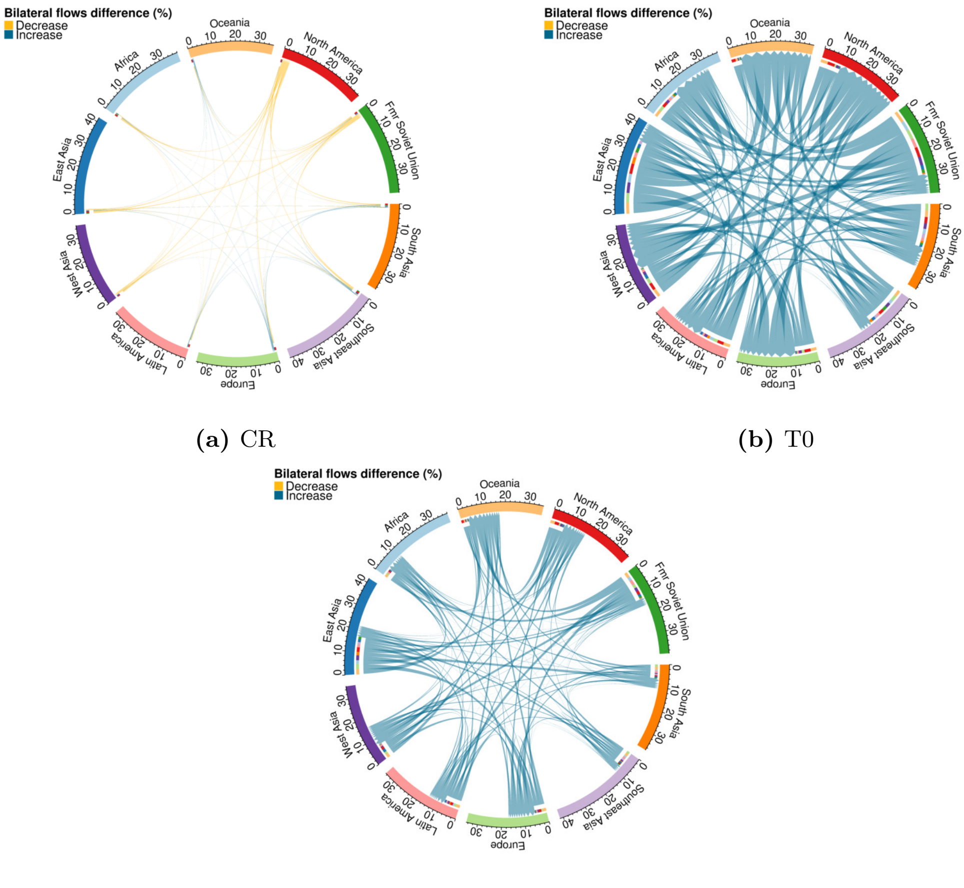
Figure C.3: As in Figure 4.5 but for the long-term impact method.



(a) CR

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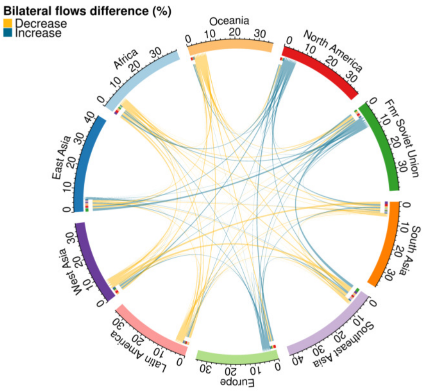
Figure C.4: As in Figure 4.6 but for the long-term impact method.



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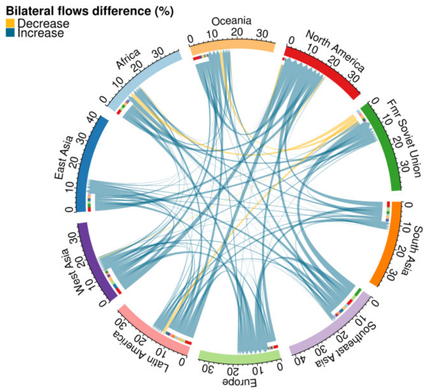

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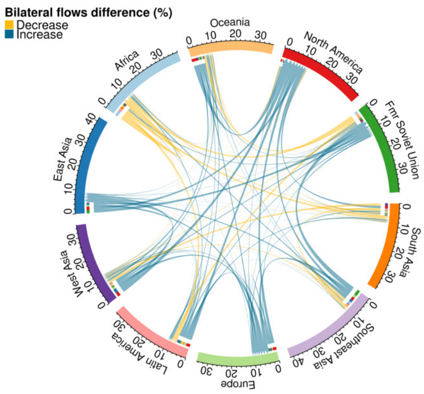

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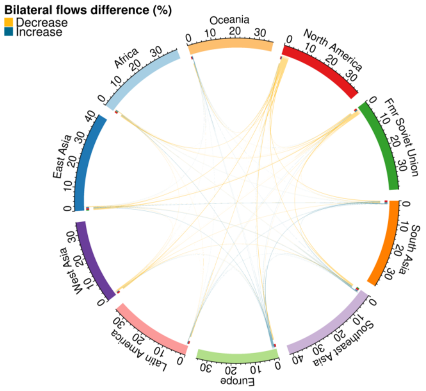
Figure C.5: As in Figure 4.6 but for SSP3-7.0.



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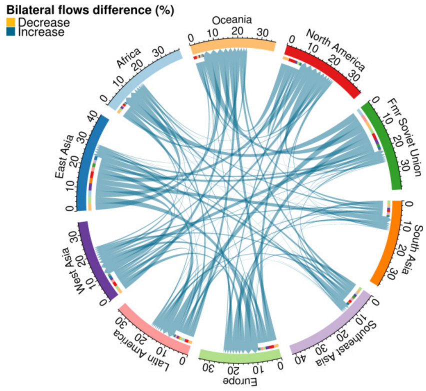

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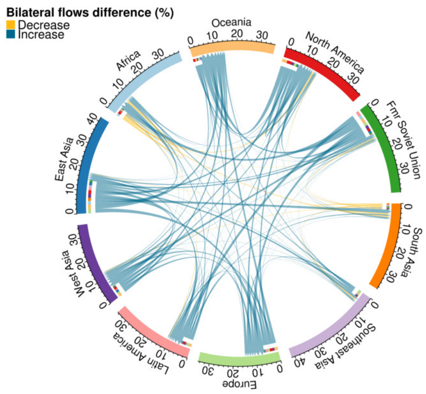

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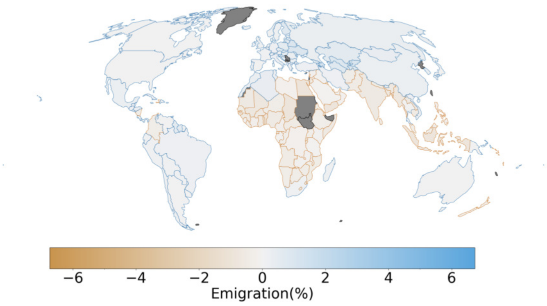
Figure C.6: As in Figure 4.6 but for SSP3-7.0 and long-term impact method.



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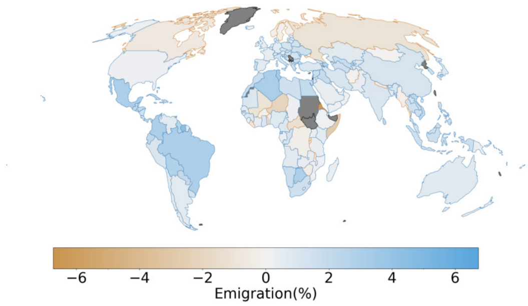

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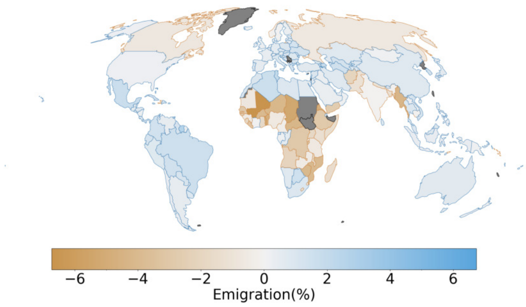

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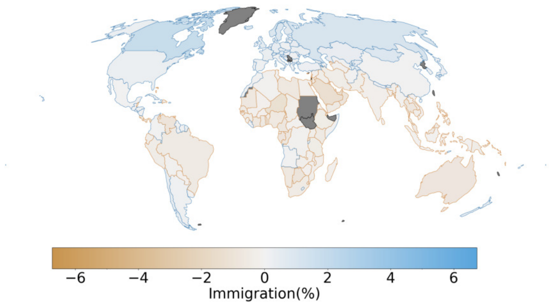
Figure C.7: As in Figure 4.4 but for the SSP3-7.0.



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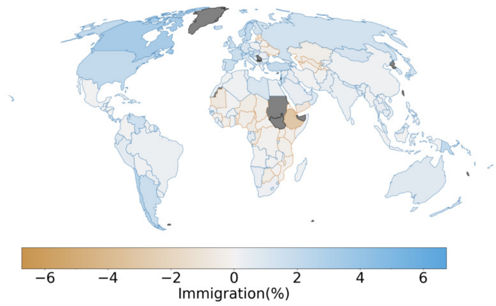

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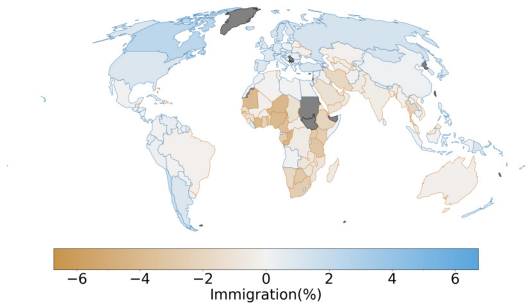

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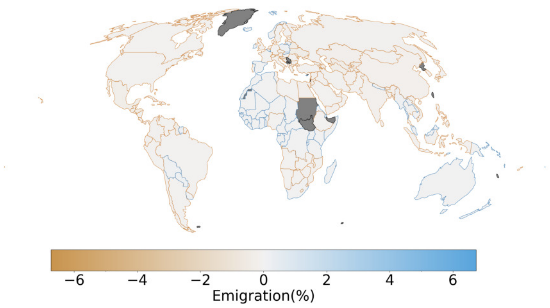
Figure C.8: As in Figure 4.5 but for SSP3-7.0.



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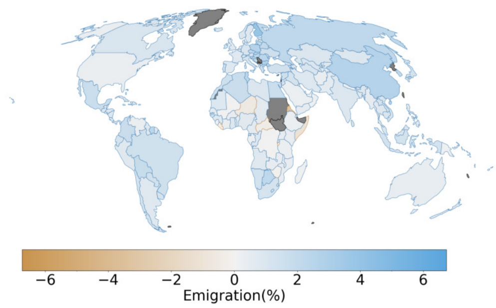

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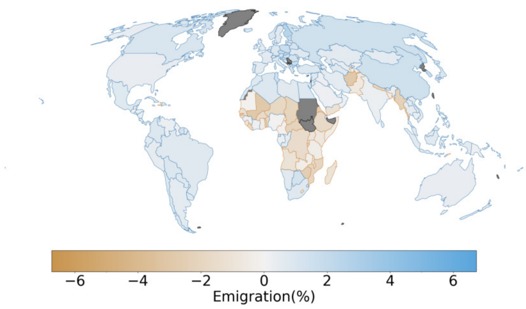

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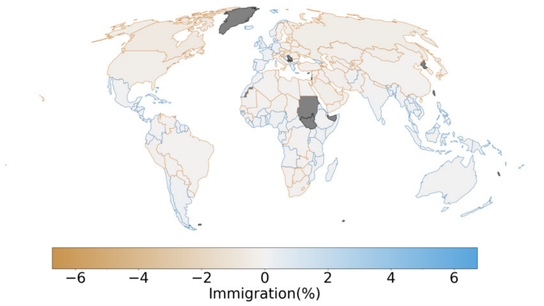
Figure C.9: As in Figure 4.4 but for the long-term method and SSP3-7.0.



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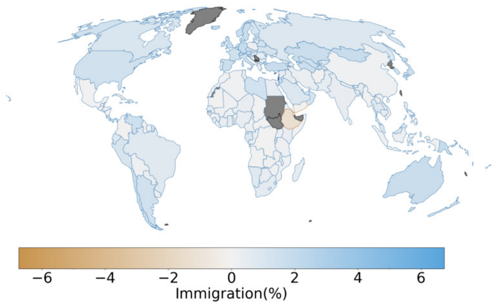

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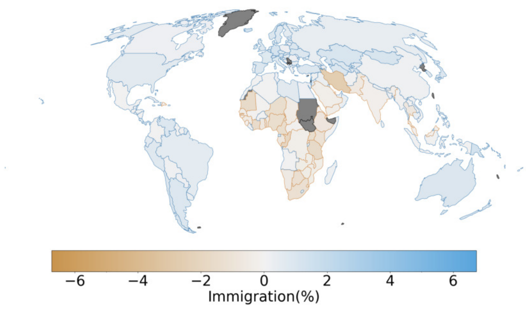

(c) TS

Figure C.10: As in Figure 4.5 but for the long-term climate change impact and SSP3-7.0.

Acknowledgements

Usually, acknowledgements are written right after having finished writing the thesis. This was also my plan, but I ended up adjusting my thesis until the last minute of the deadline. Thus, I wrote this section months after the submission and after the discussion. Perhaps, it is better this way: you have the time for realising the long path that you took and what it meant for you. Writing the aknowledgments takes me back to many moments of that path, ultimately realising the crucial importance of the people that accompanied me.

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Sebastian, zio, thank you for having been there. Sometimes all what we need is just someone that tells us: You can do this! You have been that one for me.

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"I would like to acknowledge the thousands of individuals who have coded for open-source projects for free. It is due to their efforts that scientific work with powerful tools is possible."