ENVIRONMENTAL RESEARCH
LETTERS

LETTER • **OPEN ACCESS**

Climate variability and worldwide migration: current evidence and future projections

To cite this article: Cristina Cattaneo *et al* 2024 *Environ. Res. Lett.* **19** 124083

ENVIRONMENTAL RESEARCH
LETTERS

CrossMark

OPEN ACCESS

RECEIVED
2 February 2023

REVISED
28 October 2024

ACCEPTED FOR PUBLICATION
13 November 2024

PUBLISHED
26 November 2024

LETTER

Climate variability and worldwide migration: current evidence and future projections

Cristina Cattaneo[1,2,*], Emanuele Massetti[3], Fabio Farinosi[4] and Shouro Dasgupta[1,2]

[1] CMCC Foundation - Euro-Mediterranean Center on Climate Change, Italy
[2] RFF-CMCC European Institute on Economics and the Environment, Milan, Italy
[3] IMF, Washington DC, United States of America
[4] European Commission, Joint Research Centre (JRC), Ispra, Italy
[*] Author to whom any correspondence should be addressed.

E-mail: crcattaneo@liuc.it and cristina.cattaneo@eiee.org

Keywords: climate change, international migration, Future Projections

Supplementary material for this article is available online

Abstract

The literature linking climatic drivers and migration is growing, but there is still limited evidence and substantial uncertainty regarding future bilateral flows driven by climate stress on a global scale. The aim of this paper is to fill this gap by projecting changes in the flows of international migrants from medium-term population and climate change projections. We employ a bilateral gravity equation for emigration rates controlling for decadal weather averages of temperature, precipitation, droughts, and extreme precipitation in the origin countries. We use the parameter estimates of the gravity equation to estimate global, regional, and country-by-country emigration flows for several combinations of socio-economic development and climate change. Results indicate that global emigration flows are projected to increase to around 110 million in 2060 for SSP1 and RCP 4.5 and SSP5 and RCP 4.5; to 135 million for SSP5 and RCP 8.5; to 163 million for SSP3 and RCP 4.5. We report that changes in emigration flows are largely due to population growth in the origin countries.

1. Introduction

There is ample archaeological evidence that people have migrated in response to environmental changes (Weiss and Bradley 2001, Fagan 2008, Lachniet *et al* 2017). Historical evidence has, however, little relevance for present-day societies because socio-economic conditions are very different now compared to centuries ago (Haferkamp and Smelser 1991). It is, therefore, unclear if climate change will lead to a higher number of international migrants. Understanding how people may move in response to climate change is very important because migration has both large positive and negative welfare effects on migrants, origin countries, and destination countries alike (di Giovanni *et al* 2015). Moreover, sound management of migration flows requires plans that must rely on the size of potential flows (Carammia *et al* 2022). The goal of this paper is to provide estimates of migration flows between countries in response to changes in temperature, precipitation, droughts, and excess precipitation under several socio-economic and climate scenarios. Results can support policy-makers in the difficult task of regulating migration and provide insights on possible societal challenges and macro-economic impacts from a moving labour force.

The number of studies that quantify the migration response to weather and climatic events using historical data has grown substantially in recent years, as documented by two meta-analyses (Hoffmann *et al* 2020, 2022, Beine and Jeusette 2021). However, there are few projections of climate-induced flows, and they often suffer from important limitations. Some early studies assume that migration decisions are exclusively taken to avoid climate risks, ignoring the political, economic, or demographic context (Myers 1993, 2002, Stern 2007). However, people exposed to climate hazards will not necessarily choose to migrate. The cost of migrating may be higher than the benefit, or social, economic, and political factors may constrain individual choices.

More recent studies use micro-level data to estimate the relationship between migration and climatic variables empirically, thus accounting for individual preferences and constraints such as gender, education, available resources (Bohra-Mishra *et al* 2014, Mueller *et al* 2014, Jessoe *et al* 2018, Cattaneo and Massetti 2019). These papers combine the econometric estimates with climate scenarios to predict the change in the probability of migrating, assuming everything else remains constant. While these studies can capture local specificities in response to climate shocks, we believe that being geographically narrow, cannot be used to extrapolate migration patterns globally.

Other studies extend the analysis to many countries using panel data (Marchiori *et al* 2012). These panel studies exploit the effect of relatively small, short-term, and unpredictable weather shocks to predict the impact of relatively large, long-term, and at least in part predictable climate change. Only under very restrictive assumptions the short-term weather shocks and long-term climate change have analogous impacts (Hsiang 2016), while in general, they are not the same. Not only do short-term responses and long-term responses differ, but the direction of the 'bias' is also difficult to predict (Ionesco *et al* 2016). Understanding the future potential impacts of climate change on migration requires modelling how agents adjust and adapt to a changing climate.

Finally, attempts to theoretically model the long-term implications of climate change on migration exist and have been pioneered by Desmet *et al* (2018) and Desmet and Rossi-Hansberg (2015). Building on these papers, Burzyński *et al* (2022) endogenize the effects of changing temperatures, sea levels, and the frequency and intensity of natural disasters on individual decisions to move. They predict 37, 57, and 94 million total international climate migrants over the 21st century under the RCPs 4.5, 7.0, and 8.5, respectively. These estimates represent changes in the aggregate number of migrants relative to the hypothetical scenario of no climate change, where climatic variables remain equal to the 2010 values. Desmet *et al* (2021) employ a high-resolution global dynamic equilibrium framework to measure the spatial shifts in population and economic activity only induced by coastal flooding. Their highest prediction amounts to 2.25% world population displaced in 2200 under the more extreme emissions scenario RCP 8.5. Alvarez and Rossi-Hansberg (2024) develop a global spatial dynamic assessment model incorporating agents' reactions to temperature rise through migration, trade, and investment. They predict that 600 million people will be cumulatively displaced by global warming by 2200, corresponding to approximately 5% of the world population (3 million additional migrants per year, on average)[5].

Our paper extends this literature by empirically estimating both total and bilateral flows of migrants. We use a bilateral gravity framework to produce parameter estimates of the effect of climate variables on international migration and generate global, regional, and country-by-country estimates of migration flows for several combinations of socio-economic development (shared socio-economic pathways—SSPs) and atmospheric alterations (representative concentration pathways—RCPs), spanning a wide range of future climate scenarios. We regress decadal averages in migration on decadal averages of climate. By combining changes in climate and socio-demographic conditions, we can provide information on their aggregate effect on migration flows and estimate the relative importance of socio-demographic and climate drivers.

This study improves the literature in several ways. First, by using decadal averages instead of annual data, our estimated response function can be used to predict medium-term climate change effects more accurately than with yearly fixed effects panel models (Melissa *et al* 2014). Second, we do not limit the analysis to the impacts of changes in average temperature and precipitation. Despite increasing concerns about the impacts of larger intensity and frequency of extreme weather, the literature has often neglected their effect, possibly omitting important drivers of migration. Akyapi *et al* (2022) show that extreme temperature, drought, and flood events are more important than average annual temperature in explaining GDP growth globally. Droughts and floods are also the two hydro-meteorological disasters that have historically been responsible for the largest number of deaths[6]. Our analysis continues to use average temperature and precipitation, but we also include measures of droughts and extreme precipitations that may cause floods. Third, instead of using data from disasters datasets, which infer the existence of a climate disaster from reported impacts, a potential source of endogeneity bias (Felbermayr and Gröschl 2014), we build indicators for floods and droughts using high-resolution precipitation data on the entire world. Fourth, the use of bilateral as opposed to unilateral data allows us to predict the outflows of migrants and the corresponding inflows

[5] We acknowledge, that even if migration between countries is widespread, most of the flows, including those induced by a changing climate, are expected to occur domestically. Some studies focus on predicting future migration within countries (Rigaud *et al* 2018, Peri and Sasahara 2019, Clement *et al* 2021). Our paper instead specifically focuses on predicting international migration flows.

[6] See for example the EM-DAT database.

Table 1. Summary statistics.

Variable	Obs.	Mean	Sd	Min	Max
Emigration rate—bilateral	91 305	0.126	2.342	0	291.915
Emigration flows—bilateral	91 305	1172	29 407	0	4705 677
Temperature (degree C)—unilateral	91 305	22.575	6.002	0.082	32.347
Precipitation (annual mm)—unilateral	91 305	1195	699	28	3377
Droughts (weighted number of months)—unilateral	91 305	0.222	0.269	0	1.000
Flood (mm per day)—unilateral	91 305	9.167	6.235	0	27.011

Notes: The statistic for emigration rate has been multiplied by 1000 to make the figure more readable.

of migrants in the different destination countries. We can predict specific patterns of migration induced by climate change, which has never been done before at such granularity.

The paper is organized as follows. Section 2 describes the data. Section 3 presents the methodological approach. Section 4 provides the outcomes of the empirical analyses. Section 5 provides discussion and concludes.

2. Data description

The primary data source on migration is the Global Bilateral Migration Database (Ozden *et al* 2011), which provides data on bilateral migration stock from 1960 to 2000 on a decadal basis. This dataset has been extended up to 2010 thanks to a joint effort between the OECD and the World Bank (OECD 2015). Bilateral flows are generated using the stock differencing approach as in (Beine and Parsons 2015, Cattaneo and Peri 2016). Drawing from the bilateral stock data, the emigration flows are computed as differences between stocks in two consecutive Censuses. To generate emigration rates from flows, we divide the bilateral flows by the population of the origin country, taken from the (United Nations Population Division 2015).

Historical climate data used in the analysis is from the NASA NOAH Global Land Data Assimilation System (GLDAS v2) Dataset. The dataset provides reanalysis gridded data on temperature and precipitation at 1° × 1° spatial-resolution and 3 h temporal intervals. Temperature and precipitation data at the grid cell levels are aggregated into country-year averages using 2000 population weights from the NASA's Socioeconomic Data Applications Center Gridded Population of the World (CIESIN 2018). The resulting country-level variables are then averaged over each decade.

As precipitation extremes, both floods and droughts might have a substantial impact on migration. There is little consistency in how precipitation scarcity is captured in studies of migration (see for example Dallmann and Millock 2017). In this paper, to control for drought conditions, we rely on the Standardized Precipitation Index-SPI. We compute the 12 month SPI, which is an indicator of deviations of precipitation from its long-term distribution during the preceding 12 months (McKee *et al* 1993)[7].

We calculate SPI values for all the grid cells of the GLDAS global domain. As the impact of droughts is assumed to affect migration via reduced agricultural productivity, we exclude grid cells not suitable for crops using land use data from the Global Agro-Ecological Zones database (FAO and IIASA 2022)[8]. To focus only on severe droughts, we count the number of months the SPI is below −1.5 in each grid cell with crops, as in McGuirk and Burke (2020)[9]. Finally, we aggregate at country level using population weights and then calculate decadal country averages.

To control for heavy rainfall events potentially indicating flood-like conditions, we use the 90th percentile of the annual distribution of daily precipitation in each grid cell, similarly to Chen *et al* (2017) and Mueller *et al* (2014). We use population weights to calculate yearly country averages and then calculate decadal country averages.

Table 1 presents measurement units and summary statistics of historical climate data.

The same methods are used to calculate temperature, precipitation, SPI, and flood-like conditions from gridded scenarios of future climate generated by models used for the Coupled Model Intercomparison Project Phase 5 (CMIP5). In particular, we use the ensemble mean of temperature and precipitation for medium (RCP4.5) and extreme (RCP8.5) emission scenarios from 5 climate models derived from the NASA Earth Exchange Global Daily Downscaled and Bias Corrected Projections—NEX-GDDP (Thrasher *et al* 2012). We use population data from gridded population projections developed for the SSPs (O'Neill *et al* 2017) for weighting climate variables. While the emission scenarios in the RCP4.5 can be matched with the narratives of all the five SSPs, the

[7] The choice of the 12 months SPI allows to capture longer term water deficits and hydrological droughts that could be relevant for agriculture, river discharge and groundwater recharge (Naumann *et al* 2018).

[8] Permanent pastoral areas are also not included.

[9] The reason to identify as 'severe droughts' the instances in which SPI falls below the threshold of −1.5 is explained in the WMO guidelines for the use of this index (WMO 2012) identifying respectively the interval −1.5 to −1.99 as severely dry and the −2 and less as extremely dry.

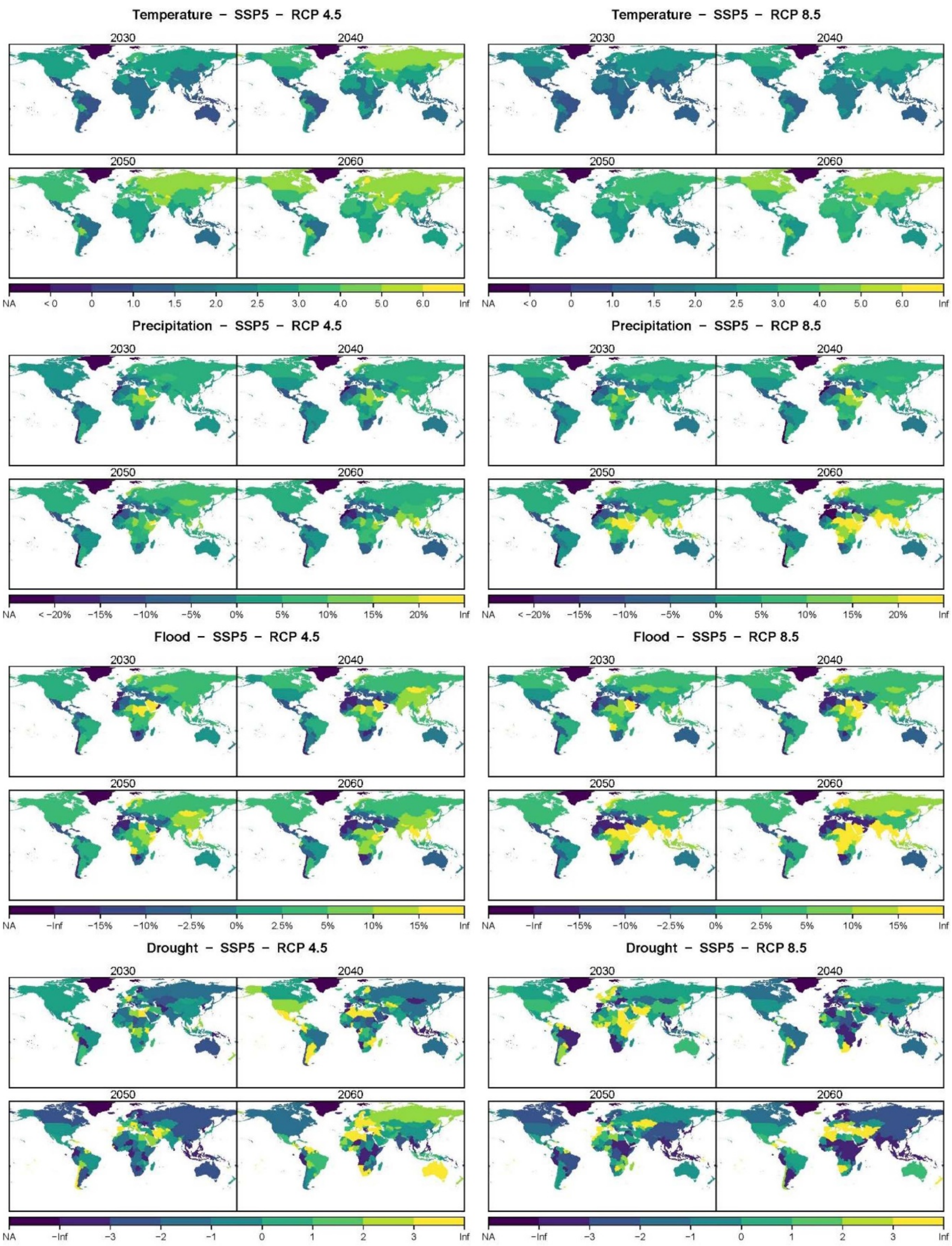

Figure 1. Change of climate variables with respect to the period 1960–2010. Climate scenarios from five Global Circulation Models (GCM) of the NASA Earth Exchange Global Daily Downscaled and bias corrected Projections (NEX-GDDP), prepared for the Coupled Model Intercomparison Project Phase 5 (CMIP5). Temperature change is measured in °C. Change in precipitations and in the occurrence of flood-like conditions in measured in percentage. Change of the drought indicator are measured in months during which the SPI has a value less than −1.5.

extreme level of emissions in RCP8.5 is compatible only with the fast growth and intensive fossil fuels use assumed in SSP5. For this reason, we match RCP4.5 with SSP1 (sustainable development), SSP3 (fragmented world) and SSP5 (fossil-fueled development), while we match the SSP5 with only the RCP8.5, as in the most recent IPCC scenario design (see, for example IPCC 2022).

Figure 1 displays changes in climate variables with respect to the period 1960–2010 for different decades and different scenarios. For the Figure, we selected SSP5 because this is the only SSP that allows us a direct comparison of climate scenarios for RCP 4.5 and RCP 8.5. Global warming is likely to intensify over time, with the increase being particularly noticeable at the higher latitudes. Changes in the global precipitation patterns are instead more varied, with some countries expected to receive more abundant rainfall and some likely to experience drier conditions. As the planet warms, the uneven distribution of precipitation patterns across countries is expected to become even more unbalanced. Extreme precipitation events are expected to increase in many countries. In several regions where total precipitation is likely to increase, the trend in occurrence of extreme precipitation events is projected to follow a similar increasing pattern. Droughts, and generally drier conditions are expected to be experienced more frequently in some regions, notably around the Mediterranean and in the Middle East. While temperature will increase in all countries and regions, in some parts of the world, both floods and droughts display declining patterns.

3. Empirical approach

We employ a bilateral gravity framework to produce parameter estimates of the effect of climate variables on international migration. Details of the estimation are presented in the supplementary material (S.1). As the climate is likely to play a minor role in explaining migration from richer countries (Cai *et al* 2016), we follow Cattaneo and Peri (2016) and exclude from the sample the top 20% of countries in the GDP per capita distribution, which are receivers of the flows[10]. The final sample includes 100 origin and 203 destination countries. See supplementary material (S.2) for the complete list of countries. The period of the analysis runs from 1960 to 2010, meaning that the flows are computed over the decades, starting from $t = 1960$ up to $t = 2000$.

Once the parameters are estimated using the historical data, we generate future emigration rates using the scenario of future temperature, precipitation, SPI and flood-like conditions. This is a *ceteris paribus* exercise because we assume that all the other driving factors of migration remain unchanged. To incorporate parameter uncertainty from our statistical model, we generate bootstrap confidence intervals from 1000 repetitions of this exercise of the empirical model[11]. Finally, we transform the prediction of migration rates ($\hat{y}_{ijT}$) into migration flows (M_{ijT}) by multiplying times the population levels in each origin country. We use population data for different SSPs scenarios ($N_{ii,T}$),

$$M_{ijT} = \hat{y}_{ijT} * N_{ii,T}.$$

[10] Results are robust to different cut-off points.

[11] We employ the command bsample in Stata, which is the statistical software used for the estimations. The command draws a sample with replacement from the original dataset.

Table 2. Historical estimations.

	(1)	(2)	(3)
	only T	no P	All
ln(temperature)	1.898***	1.564**	1.582**
	(0.691)	(0.624)	(0.615)
ln(precipitation)			0.266
			(1.140)
Drought		0.324**	0.337**
		(0.147)	(0.166)
Flood		0.153**	0.138
		(0.071)	(0.096)
Observations	91 305	91 305	91 305
Origin FE	Yes	Yes	Yes
Destination*decade FE	Yes	Yes	Yes
Pair FE	Yes	Yes	Yes
Pseudo-R2	0.8623	0.8629	0.8629
P-Val Wald T Climate	0.0060	0.0002	0.0005

Notes: the dependent variable is the emigration rate from country, i to country j, in decade t. Method of estimation is PPML. Reference periods for the analysis: 1960-2010. Standard errors, clustered at origin levels, in parentheses. *** p<0.01, ** p<0.05, * p<0.1. The P-Value of a Wald Test on the coefficient of Precipitation is 0.816.

4. In-sample results and projections

Table 2 presents the results for the gravity equation, employing increasingly saturated specifications, as described in equation (1) of supplementary material S.1. Across all three specifications, the estimated parameters for temperature are consistent in magnitude and significance. The point estimates indicate that if temperature increases by 1%, bilateral migration rates increase by 1.9 (Column 1), and 1.6% (Columns 2 and 3) over a decade. Average precipitation is not an important driver of migration, as indicated by the non-statistically significant coefficient. If we exclude precipitation from the regression (Column 2), the coefficient of temperature remains robust. The coefficient of droughts is positive with and without the inclusion of precipitation. Finally, flood exerts a positive and statistically significant effect on emigration rates, but the coefficient turns non-statistically significant in column (3). Results indicate that temperature is a robust factor that drives migration, which confirms the conclusion from a meta-analysis that temperature-level changes exert the strongest effects on migration (Hoffmann *et al* 2020). We provide additional results and sensitivity checks in table S.3 of the supplementary material.

The bottom of the table reports Pseudo-R2, which we use to compare the three specifications and select the one to be used to project migration flows. It also provides the result of a Wald Test on the climatic variables, to detect if our specifications provide a better fit

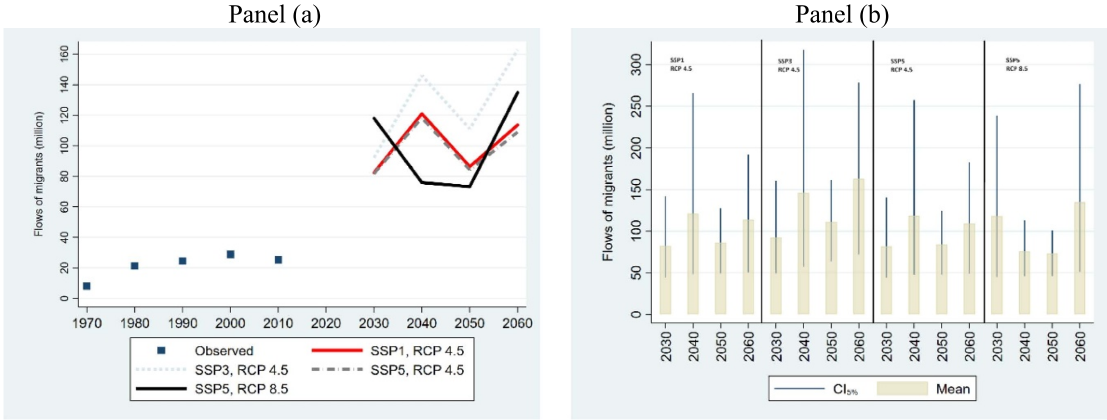

Figure 2. Historical and predicted global outflows of climate migrants. We use the parameter estimates from column (3) of table 2 to generate projections of migration flows due to climate and population change. Panel (a): blue square dots show the observed historical flows. Panel (b): the bars show predicted flows, whereas the lines illustrate 95% bootstrap confidence intervals.

compared to a model with only fixed effects[12]. While specifications in Columns (2) and (3) display the same Pseudo-R2, a Wald test that compares if model (3) fits significantly better than model (2) provides support to the most parsimonious model in (2)[13]. Therefore, we use the parameters of Column (2) to generate total global flows of migrants, flows by country and bilateral flows among continents.

Panel (a) of figure 2 displays the predicted future flows of migrants until 2060 together with the observed decadal flows from 1970 to 2010. Panel (b) presents the same estimates, by scenario and year, with 95% bootstrap confidence intervals. The total number of international migrants for the pairs of 100 origins and 203 destinations covered by our study is expected to increase in all scenarios. The size of the increase will depend on the scenario. For example, the total decadal flows will increase from 30 million in 2010 to around 110 million in 2060 for SSP1 and RCP 4.5 and SSP5 and RCP 4.5, to 135 million for the SSP5 and RCP 8.5 and to 163 million for the SSP3 and RCP 4.5. As a comparison, supplementary material S.4 (table S.3 and figure S.1) presents the global flows of migrants produced using all specifications (only *T*, no *P* and All). The projections from two specifications, namely the ones that include drought and flood (All and no *P*) produce similar results, while the one that only uses temperature variation produces a lower bound projection (only *T*).

The gap between the observed flows up to 2010 and the predictions of the model from 2030 onward can be explained by the growing population combined with a rising temperature and the intensification of extreme events, such as droughts and floods.

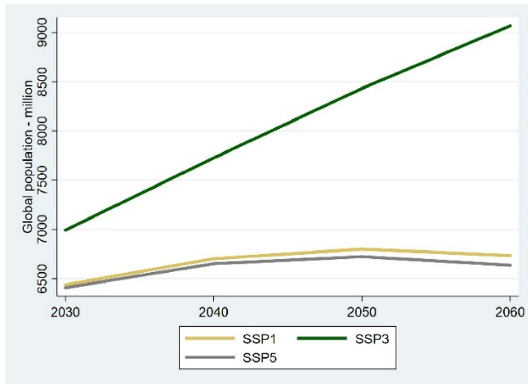

Figure 3. Population projections. The numbers are computed by aggregating the population projections of the origin countries included in the sample. See appendix B for the complete list of countries.

SSP3 combined with RCP 4.5, the high-population growth scenario (figure 3), has the largest migration flows in almost all decades, while SSP1 combined with RCP 4.5 and SSP5 combined with 4.5, with identical climate but lower population growth, are at the bottom of the range.

We gain a more accurate assessment of the relative importance of population and climate scenarios by decomposing the effect of a changing climate from the effect of a changing population on future migration flows. First, we predict emigration rates using climate change scenarios, but we use the historical population in the origin country. Second, we predict emigration rates using the historical average climate over the panel decades, but we allow the population to grow. The results of these two exercises are displayed in figure 4. Population growth is responsible for a large increase in migration over time and across scenarios. The number of migrants when

[12] The performance of the Wald test is low in the case of multicollinearity. For this reason, we checked the correlation between the set of climatic variables included in the full model. The correlation coefficients are low, suggesting that multicollinearity is not an issue in our case.

[13] The Wald test is used to evaluate if constraining a parameter to be zero significantly reduces the fit of the model and it is therefore employed to test the difference between nested models.

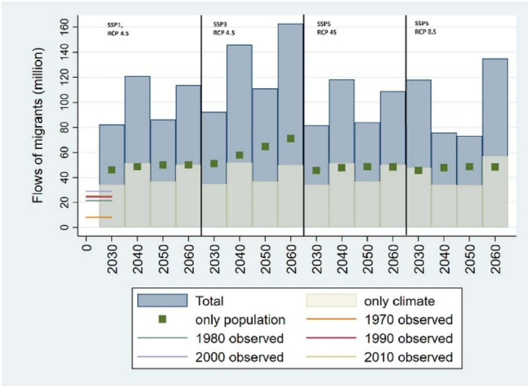

Figure 4. Global decadal outflows of climate migrants. Decomposition for climate and population. The height of the blue bars displays the projections of migration flows due to climate and population changes; the height of the grey bars displays the projections of migration flows due to only climate change; the green square dots indicate the projections of migration flows due to only population changes. Horizontal lines indicate the observed historical flows for ‘70, ‘80, ‘90, ‘00 and ‘10.

the population grows, and the climate stays constant (green square dots) is higher than the counterfactual that keeps the population constant but allows climate to change. The total vertical bars (grey plus blue) are generated by combining the future climate models and the future population projections. The strong influence of population growth on migration is in line with Dao *et al* (2021), which report that future trends in international migration are mainly driven by changes in country population size and in educational attainment.

The largest increase in migration occurs when we use the SSP3 scenario because it has the largest population growth. SSP3 describes a world with increasing inequality, fast population growth, resurgent nationalism and policies strongly oriented toward national and regional security issues. Therefore, the SSP3 narrative assumes closed borders and a low level of migration. Given that we do not impose on our projections an exogenous cap on migration but assume that international migration policy in destinations follows their historical trend, our study finds more future migration under the SSP3 compared to the narrative described under the SSP3 scenario.

Total migration flows displayed in figures 2 and 4 are obtained by summing projected flows from the sample of countries with outmigration. The rich bilateral nature of the data allows us to dive deep into the results and disaggregate the projected flows by specific origin countries and by pairs of origins and destinations. This is an important contribution of the paper to the literature. By predicting both inflows and outflows, we provide useful information to assess the exposure of both origin and destination areas.

One way to look at our results is to focus on emigration flows by specific origin countries. In particular, figure 5 displays the changes in migration projections in 2030 compared to the observed flows in 2010 for the SSP3 and RCP 4.5 scenarios. If we let both climate and population change (left panel), the projected climate-induced migration flows are projected to increase significantly in many countries, particularly African and, to a smaller extent, Asian countries. If we keep the population at the 2010 level and let only climate change (right panel), the percentage change in migration is smaller, as expected from the global analysis. In some countries, emigration is also expected to decline. The differences in projections that we observe between countries are due to the projected differences in country-level drought and flood, as described in figure 1.

Another way to present the result is by showing bilateral projections. Figure 6 displays the projected bilateral flows within and between continents in 2030, assuming that both climate and population change, as in the SSP3 and RCP 4.5 scenario. We find that the migration flows are projected to increase for all pairs of continents. However, the largest increase in migration flows will be bounded within continents, namely within African and Asian countries. Flows from Africa to Europe will double, from 2.5 million in 2010 to 6 million in 2030. Flows from Asia to Europe will reach 6.7 million in 2030, against the 3.2 million in 2010. Flows from Asia to North America will increase from 3.3 million to 9.4 million.

5. Discussion and conclusion

Migration has been largely used as an adaptation strategy to cope with the climate change impacts (Hoffmann *et al* 2020, Beine and Jeusette 2021) and understanding how many people will leave the origin countries for climate related reasons will assist destination countries in managing these flows (Carammia *et al* 2022). In this paper, we employ historical data that span over five decades in a bilateral gravity equation. By estimating medium-term climate change effects and combining these estimates with scenarios of climate and socio-demographic conditions, this paper contributes to predicting global emigration flows due to climate change and decomposing the contribution of population and climate-related drivers.

The world is getting warmer, and extreme events are expected to intensify. These phenomena contribute to driving emigration but demographic factors are likely to play a more important role than climate change. Our results indicate that population growth is the most important driver of long-term migration patterns.

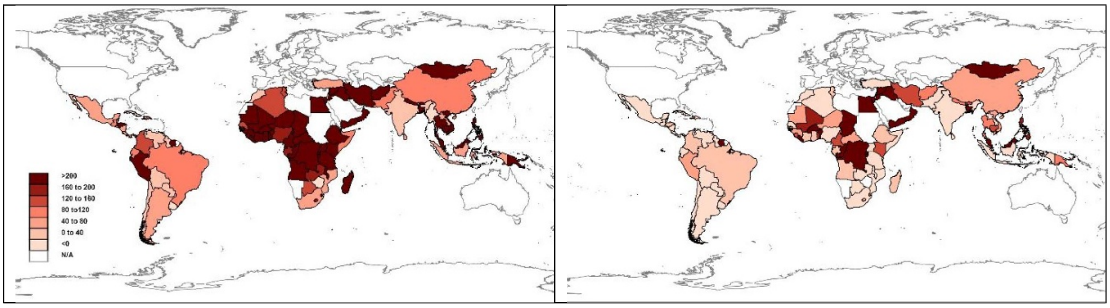

Figure 5. Percentage change in outflows compared to historical outflows. Year 2030. Projections of changes in migration outflows due to climate and population change (left panel) and only climate change (right panel). Scenarios under SSP3 and RCP 4.5.

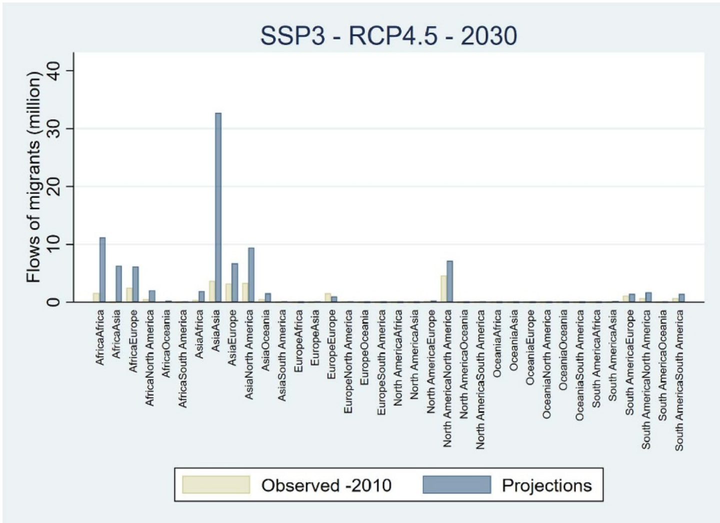

Figure 6. Bilateral flows by continent. SSP3, RCP 4.5. Year 2030. Blue bars display the projections of migration flows due to climate and population changes; light grey bars display historical flows.

Our finding is in sharp contrasts with early studies that based their projections on the number of people that live in areas 'at-risk' of climate events (Myers 1993, 2002, Stern 2007) and which predicted massive future flows. If our model is correct, there is no evidence that OECD and other net receiver countries will face large waves of climate migrants in the coming decades.

A large part of climate-related migration may also occur within countries, probably because populations affected by natural disasters tend to move only temporarily, or due to restrictions to cross-border migration (Rigaud *et al* 2018, Cattaneo *et al* 2019, Peri and Sasahara 2019, Clement *et al* 2021).

Restrictive border policies, by limiting the possibility of leaving areas more exposed to climate change, do not contribute to reducing vulnerability to climate change impacts (Benveniste *et al* 2020). Policies to facilitate temporary migration in the case of extreme events would be beneficial. If destination countries are concerned about increasing migration flows, they can implement policies that lead to slower population growth and higher economic development in origin countries. For example, investing in women's empowerment can boost economic development and result in slower population growth.

The exercise we run is informative, but it should be interpreted with caution. First, we are assuming that only climate and population will change, while future migration will be strongly affected by socio-economic developments in both origin and destination countries, technology, and policy. Second, the further we go into the future (2060) and the more pessimistic the climate scenario (RCP 8.5), the larger the long-term difference of climate variables with respect to their historical level compared to the observed variance over the estimation period. In other words, for scenarios of very high warming in the far future, we push our model considerably out-of-sample. It is not easy to predict the direction of the bias. Historical temperature change is often small and may not capture disruptive or highly nonlinear responses that may occur with much larger temperature changes. If this is the case, we underestimate the responsiveness of migration to future climate. Alternatively, the projections might have a positive bias if, for example, a permanent warming scenario will induce countries to engage in forms of adaptation, which our model does not capture well.

Data availability statement

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

Acknowledgments

We are thankful to participants of the Imf-FAD Seminar Series; the 'On the Frontier' seminar organized by Prometeia; the KDI School-World Bank DIME Conference on Impact Evaluation in Development amid Overlapping Crises; the Webinar series on The Economics of Migration; the 4th Annual LSE Workshop in Environmental Economics; and the Migration, Trade, and Human Development Rethinking Global Inequalities Conference organized by the Tower Center/Owens Foundation

ORCID iDs

Cristina Cattaneo https://orcid.org/0000-0001-8273-0143
Emanuele Massetti https://orcid.org/0000-0003-1659-7051
Fabio Farinosi https://orcid.org/0000-0002-4774-4854
Shouro Dasgupta https://orcid.org/0000-0003-4080-8066

References

Akyapi B, Bellon M M and Massetti E 2022 *Estimating Macro-Fiscal Effects of Climate Shocks from Billions of Geospatial Weather Observations* (International Monetary Fund)

Alvarez J L C and Rossi-Hansberg E 2024 The Economic Geography of Global Warming *Rev. Econ.* **91** 899–939

Beine M and Jeusette L 2021 A meta-analysis of the literature on climate change and migration *J. Demogr. Econ.* **87** 293–344

Beine M and Parsons C 2015 Climatic factors as determinants of international migration *Scand. J. Econ.* **117** 723–67

Benveniste H, Oppenheimer M and Fleurbaey M 2020 Effect of border policy on exposure and vulnerability to climate change *Proc. Natl Acad. Sci.* **117** 26692–702

Bohra-Mishra P, Oppenheimer M and Hsiang S M 2014 Nonlinear permanent migration response to climatic variations but minimal response to disasters *Proc. Natl Acad. Sci.* **111** 9780–5

Burzyński M, Deuster C, Docquier F and de Melo J 2022 Climate change, inequality, and human migration *J. Eur. Econ. Assoc.* **20** 1145–97

Cai R, Feng S, Oppenheimer M and Pytlikova M 2016 Climate variability and international migration: the importance of the agricultural linkage *J. Environ. Econ. Manage.* **79** 135–51

Carammia M, Maria Iacus S and Wilkin T 2022 Forecasting asylum-related migration flows with machine learning and data at scale *Sci. Rep.* **12** 1457

Cattaneo C, Beine M, Fröhlich C, Kniveton D, Martinez-Zarzoso I, Mastrorillo M, Millock K, Piguet E and Schraven B 2019 Human migration in the era of climate change *Rev. Environ. Econ. Policy.* **13** 189–206

Cattaneo C and Massetti E 2019 Does harmful climate increase or decrease migration? Evidence from rural households in Nigeria *Clim. Change Econ.* **10** 1950013

Cattaneo C and Peri G 2016 The migration response to increasing temperatures *J. Dev. Agric. Econ.* **122** 127–46

Chen J J, Mueller V, Jia Y and Tseng S KH 2017 Validating migration responses to flooding using satellite and vital registration data *Am. Econ. Rev.* **107** 441–5

CIESIN 2018 Gridded population of the world, version 4 (GPWv4): population density adjusted to Match 2015 revision UN WPP Country totals, revision 11. NASA socioeconomic data and applications center (SEDAC) (Center for International Earth Science Information Network, Columbia University)

Clement V, Rigaud K K, de Sherbinin A, Jones B, Adamo S, Schewe J, Sadiq N and Shabahat E 2021 *Groundswell Part 2: Acting on Internal Climate Migration* (World Bank) (available at: https://openknowledge.worldbank.org/handle/10986/36248)

Dallmann I and Millock K 2017 Climate variability and inter-state migration in India *CESifo Econ. Stud.* **63** 560–94

Dao T H, Docquier F, Maurel M and Schaus P 2021 Global migration in the twentieth and twenty-first centuries: the unstoppable force of demography *Rev. World Econ.* **157** 417–49

Desmet K, Kopp R E, Kulp S A, Krisztián Nagy D, Oppenheimer M, Rossi-Hansberg E and Strauss B H 2021 Evaluating the economic cost of coastal flooding *Am. Econ. J.* **13** 444–86

Desmet K, Nagy D K and Rossi-Hansberg E 2018 The geography of development *J. Political Econ.* **126** 903–83

Desmet K and Rossi-Hansberg E 2015 On the spatial economic impact of global warming *J. Urban Econ.* **88** 16–37

di Giovanni J, Ortega F and Levchenko A A 2015 A global view of cross-border migration *J. Eur. Econ. Assoc.* **13** 168–202

Fagan B 2008 *The Great Warming: Climate Change and the Rise and Fall of Civilizations* (Bloomsbury Publishing USA)

FAO, and IIASA 2022 Global agro ecological zones version 4 (GAEZ V4)

Felbermayr G and Gröschl J 2014 Naturally negative: the growth effects of natural disasters *J. Dev. Agric. Econ.* **111** 92–106

Haferkamp H and Smelser N 1991 *Social Change and Modernity* (University of California Press)

Hoffmann R, Dimitrova A, Muttarak R, Crespo Cuaresma J and Peisker J 2020 A meta-analysis of country-level studies on environmental change and migration *Nat. Clim. Change* **10** 904–12

Hoffmann R, Wiederkehr C, Dimitrova A and Hermans K 2022 Agricultural livelihoods, adaptation, and environmental migration in Sub-Saharan drylands: a meta-analytical review *Environ. Res. Lett.* **17** 083003

Hsiang S 2016 Climate econometrics *Annu. Rev. Resour. Econ.* **8** 43–75

Ionesco D, Mokhnacheva D and Gemenne F 2016 *The Atlas of Environmental Migration* 1st edn (Routledge)

IPCC 2022 Climate change 2022: impacts, adaptation, and vulnerability. *Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press)

Jessoe K, Manning D T and Taylor J E 2018 Climate change and labour allocation in rural Mexico: evidence from annual fluctuations in weather *Econ. J.* **128** 230–61

Lachniet M S, Asmerom Y, Polyak V and Pablo Bernal J 2017 Two millennia of mesoamerican monsoon variability driven by pacific and atlantic synergistic forcing *Quat. Sci. Rev.* **155** 100–13

Marchiori L, Maystadt J F and Schumacher I 2012 The impact of weather anomalies on migration in Sub-Saharan Africa *J. Environ. Econ. Manage.* **63** 355–74

McGuirk E and Burke M 2020 The economic origins of conflict in Africa *J. Political Econ.* **128** 3940–97

McKee T B, Doesken N J and Kleist J 1993 The relationship of drought frequency and duration to time scales *8th Conf. on Applied Climatology, Anaheim* pp 179–84

Melissa D, Jones B F and Olken B A 2014 What do we learn from the weather? The New climate–economy literature *J. Econ. Lit.* **52** 740–98

Mueller V, Gray C and Kosec K 2014 Heat stress increases long-term human migration in rural Pakistan *Nat. Clim. Change* **4** 182–5

Myers N 1993 Environmental refugees in a globally warmed world *BioScience* **43** 752–61

Myers N 2002 Environmental refugees: a growing phenomenon of the 21st Century *Phil. Trans. R. Soc.* B **357** 609–13

Naumann G, Alfieri L, Wyser K, Mentaschi L, Betts R A, Carrao H, Spinoni J, Vogt J and Feyen L 2018 Global changes in drought conditions under different levels of warming *Geophys. Res. Lett.* **45** 3285–96

O'Neill B C *et al* 2017 The roads ahead: narratives for shared socioeconomic pathways describing world futures in the 21st century *Glob. Environ. Change* **42** 169–80

OECD 2015 Development of DIOC and DIOC-E over time (Organisation for Economic Co-operation and Development) (available at: www.oecd-ilibrary.org/social-issues-migration-health/connecting-with-emigrants/development-of-dioc-and-dioc-e-over-time_9789264239845-table1-en)

Ozden C, Parsons C R, Schiff M and Walmsley T L 2011 Where on Earth is everybody? The evolution of global bilateral migration 1960–2000 *World Bank Econ. Rev.* **25** 12–56

Peri G and Sasahara A 2019 The impact of global warming on rural-urban migrations: evidence from global big data *Working Paper* 25728 (National Bureau of Economic Research) (https://doi.org/10.3386/w25728)

Rigaud K K *et al* 2018 *Groundswell: Preparing for Internal Climate Migration* (World Bank)

Stern N 2007 *The Economics of Climate Change: The Stern Review* (Cambridge University Press) (https://doi.org/10.1017/CBO9780511817434)

Thrasher B, Maurer E P, McKellar C and Duffy P B 2012 Technical note: bias correcting climate model simulated daily temperature extremes with quantile mapping *Hydrol. Earth Syst. Sci.* **16** 3309–14

United Nations Population Division 2015 World population prospects: the 2015 revision *United Nations, Department of Economic and Social Affairs* (United Nations) (available at: https://population.un.org/wpp/)

Weiss H and Bradley R S 2001 What drives societal collapse? *Science* **291** 609–10

WMO, Mark 2012 Standardized precipitation index user guide *WMO N 1090* (available at: https://library.wmo.int/records/item/39629-standardized-precipitation-index-user-guide)