CLIMATE CHANGE AND HUMAN MOBILITY

Quantitative evidence on global historical trends and future projections

IOM UN MIGRATION | GLOBAL DATA INSTITUTE

1 | EXECUTIVE SUMMARY

- Global human mobility in the context of climate change and associated environmental degradation and disasters has become a subject of high-level political interest. There is strong demand for evidence-based quantitative understanding of how climate has affected mobility thus far and how it may do so in future. Whilst there has been substantial progress on projecting future global human exposure to climate-related hazards (heat waves, floods, droughts, wildfires, crop failure, sea level rise) in coming decades, the likely mobility responses to these hazards remain overall poorly understood.

- Several widely-circulated predictions of climate-related migration in the late 1990s and early 2000s have either failed to materialise or have been characterised as alarmist and lacking scientific rigour. More rigorous quantitative models of historical and projected future climate mobility at the global scale have been developed since the late 2000s; however, these have produced a range of results that are not always consistent with one another. A majority of models indicate that certain climate-related factors have *some* effect on migration, but there is no quantitative agreement on *how strong* that effect is or, in some cases, even whether the effect is positive or negative.

- Simplistic modelling techniques are likely a key bottleneck for quantitatively understanding global climate mobility. Recent years have seen the emergence of a new generation of models showing high potential for filling knowledge gaps, though, these are at too early a stage of development to provide insights robust enough to inform policy measures.

- There is scientific consensus that climatic changes, in interaction with various economic, political, and social factors, will have significant impacts on human mobility; however, the temporal, spatial, and societal dimensions of these impacts remain deeply uncertain. Further, until now, modelling approaches have not yielded projections that enable concrete actions to avert and minimise the adverse effects of climate change impacts. Identifying actionable research questions, using state-of-the-art modelling techniques, defining standardised forecasting protocols, and compiling better data – most importantly on internal mobility – can contribute to operationalisable insights, and will require concerted and coordinated efforts by the research community and data collectors to inform discussions on ways to address climate change and human mobility.

2 | GLOSSARY

CLIMATE AND WEATHER
describe related concepts that differ with regard to time scale. *Weather* refers to variations in atmospheric conditions from one hour, day, or season to the next, while *climate* refers to long-term patterns (often 30-year averages). *Climate change* refers to a change in the state of the climate identifiable by long-term changes in the mean and/or variability of its properties. It may be due to natural internal processes or external forcings including anthropogenic changes in the composition of the atmosphere or in land use.

HAZARDS
are processes, phenomena, or human activities that may cause loss of life, injury or other health impacts, property damage, social and economic disruption, or environmental degradation.

RISK
is a function of biophysical disruption (hazard) and of the exposure and vulnerability of a population; i.e., if a disruption occurs but does not expose a human population or assets of importance to that population, then the disruption may not present a risk to human society.

SUDDEN-ONSET EVENTS
are discrete occurrences with an immediate impact, and typically last hours or days. Examples include storms, floods, heat waves, and wildfires.

QUANTITATIVE MIGRATION MODELS
are mathematical descriptions of the relationship between human mobility (e.g., measured in terms of migration flows) and relevant driver variables (e.g., income levels, age structures, climatic conditions, etc. in places of origin and destination). Models are developed and evaluated based on historical data. The simplest and most widely-used examples are linear models, which assume that a change in some variable (e.g., income) always has the same (increasing or decreasing) effect on mobility, no matter the context. Nonlinear models allow for more complex relationships (e.g., income increasing mobility in some contexts and decreasing it in others).

REPRESENTATIVE CONCENTRATION PATHWAYS (RCPS) AND SHARED SOCIOECONOMIC PATHWAYS (SSP)
are sets of plausible alternative scenarios about future atmospheric greenhouse gas concentrations and major socio-economic developments, respectively. They have been developed jointly by the research community and are used to explore the implications of each scenario for downstream processes, including human mobility, in future decades.

PROJECTIONS
are potential future evolutions of a quantity (e.g., migration flows). Projections are conditional on assumptions concerning, for example, future greenhouse gas concentration (RCP) or socio-economic (SSP) scenarios. As such, they differ from *predictions*, which refer to estimates of the most likely (often short-term) continuation of an historical trend. The term *forecasts* encompasses both projections and predictions.

INTRODUCTION

Human mobility in the context of climate change has been a subject of substantial political interest and controversy, fuelled in part by a series of ever-higher estimates of future climate-related forced migration introduced between 1995 and 2010 (Christian Aid, 2007; Biermann and Boas, 2010; Myers, 2002; Myers and Kent, 1995; Stern and Stern, 2007). Whilst these predictions have since been refuted, citing lack of methodological transparency and scientific rigour (Bettini, 2017; Gemenne, 2011), gloomy images of mass movements of 'climate migrants' persist in media and political discourses. Although most mobility related to environmental factors observed thus far has taken place within countries (Clement et al., 2021), the notion of large-scale cross-border migration towards the 'Global North' in response to climatic changes has attracted particular attention (Boas, 2015; Boas et al., 2019; Cattaneo et al., 2019), spurred by attributions of recent large-scale international migration events, including from Syria in 2015 and from Central America in 2018, to adverse climatic conditions (Gleick, 2014; Kelley et t al., 2015; New York Times and Lustgarten, 2020). Subsequent research has once again put these lines of argument into question (Boas et al., 2019; Borderon et al., 2019; Omobowale et al., 2019; Zickgraf, 2019), illustrating the current, at times polarised, dynamics of the space (Borderon et al., 2019; Piguet, Kaenzig, and Guélat, 2018; Klepp, 2017).

The magnitude of worldwide displacements triggered by weather-related events today illustrates the importance of developing a better understanding of the relationship between climate hazards and human mobility. New internal displacements due to storms, floods, wildfires, droughts, and extreme temperatures have been estimated at 21.9 million annually across the past decade (31.8 million in 2022) (IDMC, 2022) (Figure 1a), amounting to more than twice as many as those attributed to conflict.

Figure 1: Worldwide annual weather-related displacements in millions (2013 – 2022 average).
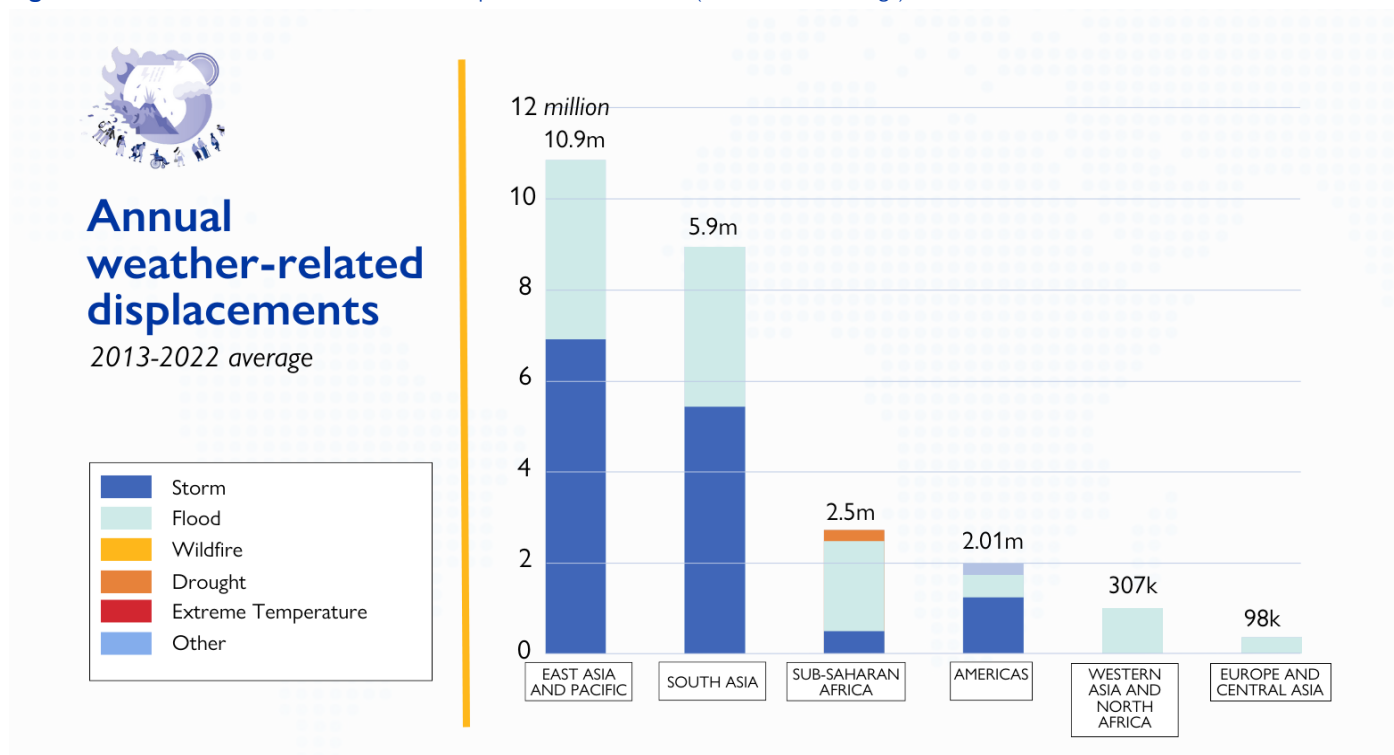
Source: Own work based on data from IDMC (2023).

Whilst over three quarters of events were recorded in East Asia, South Asia, and the Pacific, climate- and weather-related displacements affect all parts of the world (Figure 2). In many areas, sudden-onset climatic hazards and extreme weather events are projected to increase in frequency and severity (Pörtner et al., 2022; Stott, 2016; Lange et al., 2020). At the same time, slow-onset hazards – including temperatures beyond human comfort levels, water stress, land degradation, and sea level rise – are anticipated to affect large geographical areas in the coming years and decades (Pörtner et al., 2022; Lange et al., 2020), likely impacting socio-economic contexts with significant consequences for human mobility. Concerns are exacerbated by steep increases in population densities projected for many at-risk areas (Güneralp, Güneralp, and Liu, 2015; Neumann et al., 2015).

Forecasting if and how future exposure to climatic hazards will translate to human mobility in order to inform effective adaptation measures requires an analytical understanding of the relationship between climatic changes, socio-economic mediators, and migration responses. Quantitative models of migration aim to generate this understanding. They seek to establish statistical relationships between demographic, economic, social, political, and – since the late 2000s – environmental factors, on the one hand, and mobility patterns, on the other hand, that are valid across large spatial and temporal scales, thus extending detailed yet typically difficult-to-generalise knowledge from localised case studies (Reuveny and Moore, 2009). The compilation and curation of large quantitative datasets of internal and international mobility (De Sherbinin et al., 2015; Alessandrini, Ghio, and Migali, 2020; Abel and Cohen, 2022; Rees et al., 2017) have played a critical and lasting role in the rapid increase in the number of models (Ramos, 2016). Some approaches take a step further by using relationships inferred from historical observations to develop projections of future mobility. Analyses conducted thus far have been based on a wide range of different methodologies and data, which has led to results that are not always consistent, or even comparable, with one another. Complementing several conceptual analyses on the role of climatic drivers for human mobility (Piguet, Pécoud, and De Guchteneire, 2011; Brown, 2008; Perch-Nielsen, Bättig, and Imboden, 2008; Black, Adger, et al., 2011b; Warner et al., 2010), this report examines the state of quantitative evidence on this relationship to synthesise robust patterns and highlight open questions.

Figure 2: Global distribution of disaster-induced displacements in 2020.

Source: IDMC (2021).

4 | THE CLIMATE MOBILITY NEXUS

Whilst the notion of climate change forcing international mass displacement by rendering large geographical areas uninhabitable has been influential in some academic, advocacy, and policy circles (Bettini, 2017), research in recent decades has demonstrated the simplistic and often inaccurate nature of this framing. Instead, there is now consensus that migration decisions and outcomes are influenced by a complex combination of demographic, economic, social, political, environmental and other drivers and circumstances interacting at multiple scales, and that climatic conditions are but one factor, carrying more or less weight depending on local contexts (Boas et al., 2019; Pörtner et al., 2022; Black, Adger, et al., 2011b). Before examining the quantitative evidence on climatic effects on human mobility, this section briefly summarises – without aiming to provide a comprehensive account – key channels through which these effects manifest. For in-depth conceptual analyses, readers are referred to (Piguet, Pécoud, and De Guchteneire, 2011; Brown, 2008; Perch-Nielsen, Bättig, and Imboden, 2008; Black, Adger, et al., 2011b; Warner et al., 2010).

Changes in climate and weather can directly compromise human wellbeing and health, or destroy critical infrastructure and livelihoods, which can incentivise or force movement to safer areas. In the past two decades, storms, floods, and wildfires represented the three largest such drivers of displacements worldwide (IDMC, 2023) (Figure 1). Climate change acts upon these hazards by increasing their frequency and severity in many parts of the world (Pörtner et al., 2022; Stott, 2016; Seneviratne et al., 2012), though, the extent to which individual disasters can be attributed to climate change typically remains very difficult to assess (Stott et al., 2016; Otto, 2017). Not all direct climate-related effects on mobility are sudden-onset in nature; for example, gradual increases in maximum annual temperatures are projected to reach life-threatening levels in a number of densely populated areas in coming decades, whilst gradual sea level rise threatens inundation or increased flood exposure of low-lying settlements. If the inhabitability of such areas is expected to be compromised, then migration can become a beneficial or necessary adaptation strategy. With these mechanisms in mind, it is crucial to note that whether indeed gradual climatic changes or associated sudden extreme weather events directly increase mobility depends strongly on pre-existing local vulnerability and capacity for adaptation (Hoffmann et al., 2020; Horton et al., 2021). For example, migration from hazard-prone areas can even *decrease* when infrastructural investments to mitigate future impacts of storms, floods, extreme temperatures, or sea level rise, or to undo past impacts through rebuilding, lead to local job creation; indeed, such measures can *increase* migration to these areas (Wesselbaum and Aburn, 2019). Climate-related events can also decrease mobility at the other end of the adaptability spectrum, by removing resources required for migration, thus 'trapping' local populations (Black, Bennett, et al., 2011; Nawrotzki and DeWaard, 2018; Benveniste, Oppenheimer, and Fleurbaey, 2022; Rikani et al., 2022).

Whilst these direct effects of climate change have had, and are expected to continue to have, significant impacts on human mobility, indirect effects are likely to be important drivers of migration as well, including across country borders (Black, Adger, et al., 2011b; Beine and Parsons, 2017). Declines in agricultural productivity due to climate change-induced alterations in temperature and rainfall patterns are assumed to be a particularly important mediator of climate impacts on mobility (Cai et al., 2016; Cattaneo and Peri, 2016; Falco, Galeotti, and Olper, 2019). They can decrease livelihoods or even compromise food

security in farming-dependent areas, thereby widening socio-economic inequalities within and across geographical areas, and incentivising or necessitating livelihood diversification through migration to less impacted, often urban, areas (Moore and Wesselbaum, 2022). Cases in which agricultural decline triggers internal rural-urban migration, leading to increased pressure on labour markets in cities, and ultimately stimulating urban-urban migration across country borders (Maurel and Tuccio, 2016; Marchiori, Maystadt, and Schumacher, 2012) illustrate the complexity of indirect effects of climate change on mobility. Whilst agriculture is considered the economic sector that is most impacted by climate change, others will be significantly affected as well (Pörtner et al., 2022), leading to changes in income differentials that can influence mobility. As in the case of direct impacts, local socio-economic vulnerability and adaptative capacity play a critical role in how and if mobility responds indirectly to climatic changes. Adverse changes in agricultural productivity may lead to increased migration in middle-income groups, reduce migration options for low-income groups, and only marginally affect migration rates amongst high-income groups.

The impact of climate change on conflict, a major driver of global displacements, has been particularly controversial. Case studies have identified conflict as a moderator or mediator of adverse environmental effects (Ghimire, Ferreira, and Dorfman, 2015; Cattaneo and Bosetti, 2017; Abel et al., 2019; Burke, Hsiang, and Miguel, 2015); however, no consensus regarding universal quantifiable effects of climatic conditions on the likelihood of conflict outbreaks has emerged (Pörtner et al., 2022; Salehyan, 2008). Studies suggesting a significant relationship (Hsiang and Burke, 2014; Hsiang, Burke, and Miguel, 2013) have been challenged by rebuttal analyses (Buhaug et al., 2014).

© International Organisation for Migration, 2020

5 | HISTORICAL TRENDS

Quantitative analyses of the historical effects of climatic factors on human mobility are based on a range of different methods. Econometric models, reviewed in the first part of this section, have dominated research on climate mobility at large spatial scales (including global) during the past two decades; however, conflicting results and methodological limitations have raised questions about the insights that can be gained through these models beyond very general statements. As a result, and motivated by the increased availability of better and larger datasets, recent years have seen the emergence of innovative next-generation approaches to model climate mobility at the global scale, reviewed in the second part of the section. These make use of advanced statistical methods designed to accommodate the complex relationship between climatic factors and human mobility in order to fill gaps in the quantitative understanding of the climate mobility nexus.

5.1. Classical models

The large majority of quantitative analyses aiming to establish statistical relationships between climate and mobility at large spatial scales has appeared in the economic literature (Hoffmann, Šedová, and Vinke, 2021). Econometric methods used in these studies investigate whether some climate-related variable in the place of origin or destination has a statistically significant effect, typically assumed to be linear, on mobility, which is tested based on historical observations. Over three quarters of studies examine the effect of some measure of rainfall and temperature, whilst the remainder mostly considers the effects of disasters, including floods, storms, and droughts (Hoffmann, Šedová, and Vinke, 2021).

The complexity of interactions linking climatic changes to mobility outlined in section 4 foreshadows why this approach may be problematic. Even the relationship between temperature, rainfall, and agricultural productivity is highly nonlinear and strongly contingent upon crop, location, technology, and management (Peng et al., 2020; Elliott et al., 2015; Müller et al., 2017; Boote et al., 2013). Higher temperatures can decrease yields in warm countries but have the opposite effect in cold countries. Too little rainfall can lead to drought, too much can cause flood damage. The effect of changes in crop yield on mobility, in turn, is likely even more context-specific, depending strongly on local socio-economic and other factors. For example, declines in agricultural yields may force immobility in highly resource-constrained communities, stimulate rural-urban migration in some medium-income contexts, and have no measurable effect where suitable agricultural adaptation or income diversification are readily accessible locally (Rikani et al., 2022; Beine and Parsons, 2017; Cai et al., 2016; Cattaneo and Peri, 2016). By design, econometric models that assume linear relationships between climate and mobility, accounting for the majority of existing approaches, cannot accommodate these mechanisms.

As a result of these methodological limitations, combined with the use of different empirical migration data and geographical focus, different measures of climate-related variables, and different non-climatic variables included in models, the econometric literature has produced a range of results that are not always in agreement with one another (Beine and Parsons, 2017; Abel et al., 2019). For example, whilst some studies estimate that higher temperatures, reduced rainfall, or disasters increase internal or international migration, others find the opposite or no significant effect (Beyer, Schewe, and Abel, 2023).

Given the caveats associated with econometric approaches, notably a high sensitivity of results to researchers' choices of model specifications, the insights provided by any one model are typically limited. In particular, ceteris paribus conclusions of the type 'a 1% increase in temperature (or precipitation) increases migration by X%', proposed in a number of studies (Wesselbaum and Aburn, 2019; Beine and Parsons, 2017; Cai et al., 2016; Cattaneo and Peri, 2016; Coniglio and Pesce, 2015; Barrios, Bertinelli, and Strobl, 2006; Bohra-Mishra, Oppenheimer, and Hsiang, 2014; Peri and Sasahara, 2019) are (i) conceptually problematic given the complexity and nonlinearity of the climate-mobility relationship discussed above, (ii) do not reflect the uncertainty of the models, which oftentimes explain only a small proportion of the observed migration data, and (iii) can vary substantially across different studies (Wesselbaum and Aburn, 2019), suggesting high uncertainties in the estimated effect of climatic factors on mobility (Beyer, Schewe, and Abel, 2023).

Comprehensive reviews of econometric analyses on climate mobility have highlighted the divergent nature of findings, concluding that whilst most studies find that certain climatic variables have statistically significant effects on internal and international migration, there is overall no consensus about the quantitative strength, and in some cases even the direction, of the effects. With this said, several general, non-quantitative conclusions have emerged from a majority of large-scale studies (Boas et al., 2019; Berlemann and Steinhardt, 2017; Obokata, Veronis, and McLeman, 2014; Kaczan and Orgill-Meyer, 2020):

o Adverse environmental factors tend to have stronger effects on internal, especially rural-urban, migration than on international migration.

o Rising temperatures and, less consistently, rainfall deficits in agriculture-dependent counties (in which these climatic changes negatively affect yields) trend to increase both internal and international mobility, via decreases in agricultural wages.

o In communities living in poverty, adverse climatic changes tend to affect migration only weakly or even negatively, reflecting resource constraints that compromise the ability to move.

o Climate-related rapid-onset disasters often induce short-term internal displacement. However, there is no consistent pattern with regard to medium- and long-term migration.

o There is no robust evidence for a consistent effect of climate-related disasters on cross-border mobility.

In addition to reiterating that counterexamples to these general trends have been observed, it is important to note that a sizeable number of empirical studies is characterised by a geographical bias towards comparatively low-income countries in Africa, South Asia, and South America, whilst areas such as Europe are often unrepresented (Piguet, Kaenzig, and Guélat, 2018; Berlemann and Steinhardt, 2017).

A recent meta-analysis of econometric studies on climate mobility has formally quantified the degree of consistency of results in the literature, demonstrating that these vary substantially across studies (Hoffmann et al., 2020). With this said, the meta-analysis provides some quantitative support for the above-listed conclusions regarding the effects of climate-related factors on internal and international mobility, adding that estimated environmental impacts on migration tend to be strongest for Latin America and the Caribbean as well as Sub-Saharan Africa. However, it also showed that the magnitude of the estimated climatic effects on mobility is so small that it would practically be very difficult to attribute variations in migration flows to environmental changes or hazards, rather than other factors or ordinary variability.

In addition to the above-described inconsistencies between models, a recent analysis has more fundamentally questioned the ability of econometric models in general to explain how different drivers affect migration (Beyer, Schewe, and Lotze-Campen, 2022). The study showed that whilst these models capture the long-term average migration between countries well, they struggle to correctly explain changes in flows over time in terms of the relevant drivers. However, without the ability to explain migration dynamics in the past, models lack a crucial prerequisite for producing reliable future projections.

5.2. Next-generation models

The above review of insights on global climate mobility provided by classical econometric models echoes the conclusion drawn by Niva et al. (2021) that "[w]hile the relationships between environmental and socioeconomic drivers have been identified conceptually, the comprehensive global-scale spatial quantification of their interactions is in its infancy". Recent years have seen the emergence of several innovative modelling approaches promising a high potential for filling some of the knowledge gaps left by econometric models. A commonality of these approaches is that they feature at least two of the following three properties: In contrast to most econometric models,

(i) they do not assume linear relationships but use state-of-the-art nonlinear machine-learning methods to accommodate the complex interactions of climatic and other factors in driving mobility.

(ii) they operate not at country level, but are spatially explicit, which allows for important heterogeneities within countries in terms of climatic and socio-economic conditions.

(iii) they measure climate impacts not in terms of changes in temperature and/or precipitation, but more directly relevant metrics such as water-related risks and agricultural productivity.

Because of the relatively recent emergence of these models and their small number to date, conclusions based on them about historical patterns or future projections of climate mobility cannot yet be considered consensus; however, preliminary results provide useful baselines for follow-up efforts to build upon, refine, and expand. This section discusses seminal examples.

The analysis of Schutte et al. (2021) assessed the relative influence of climate, economic factors, and political violence on asylum applications to EU member states over time using so-called random forests. This machine-learning technique is designed to capture quantitatively how relevant drivers induce forced migration, in principle allowing for arbitrary nonlinear interactions between drivers. The approach allows for an assessment not only of how well any one of the three drivers on its own explains the observed asylum applications, but also how strong their respective weight is at different points through time (Figure 3). It revealed drought and temperature anomalies to

Figure 3: Estimated share of the annual global volume of asylum seekers in the EU best predicted by climate, economic factors, and political violence.
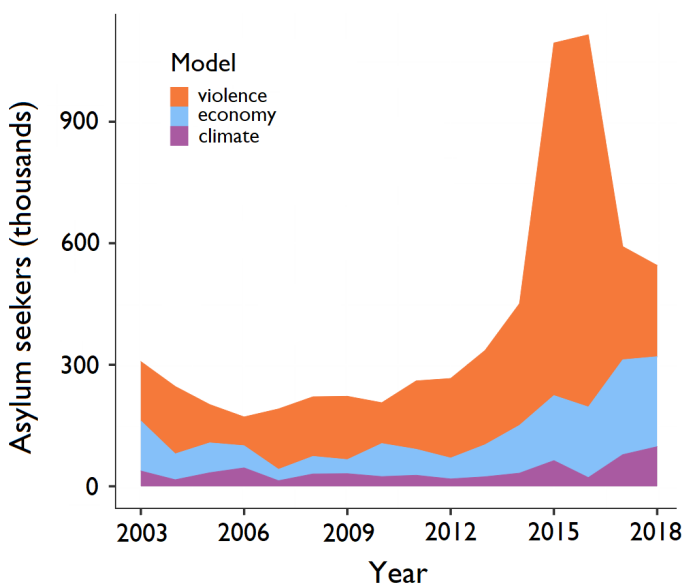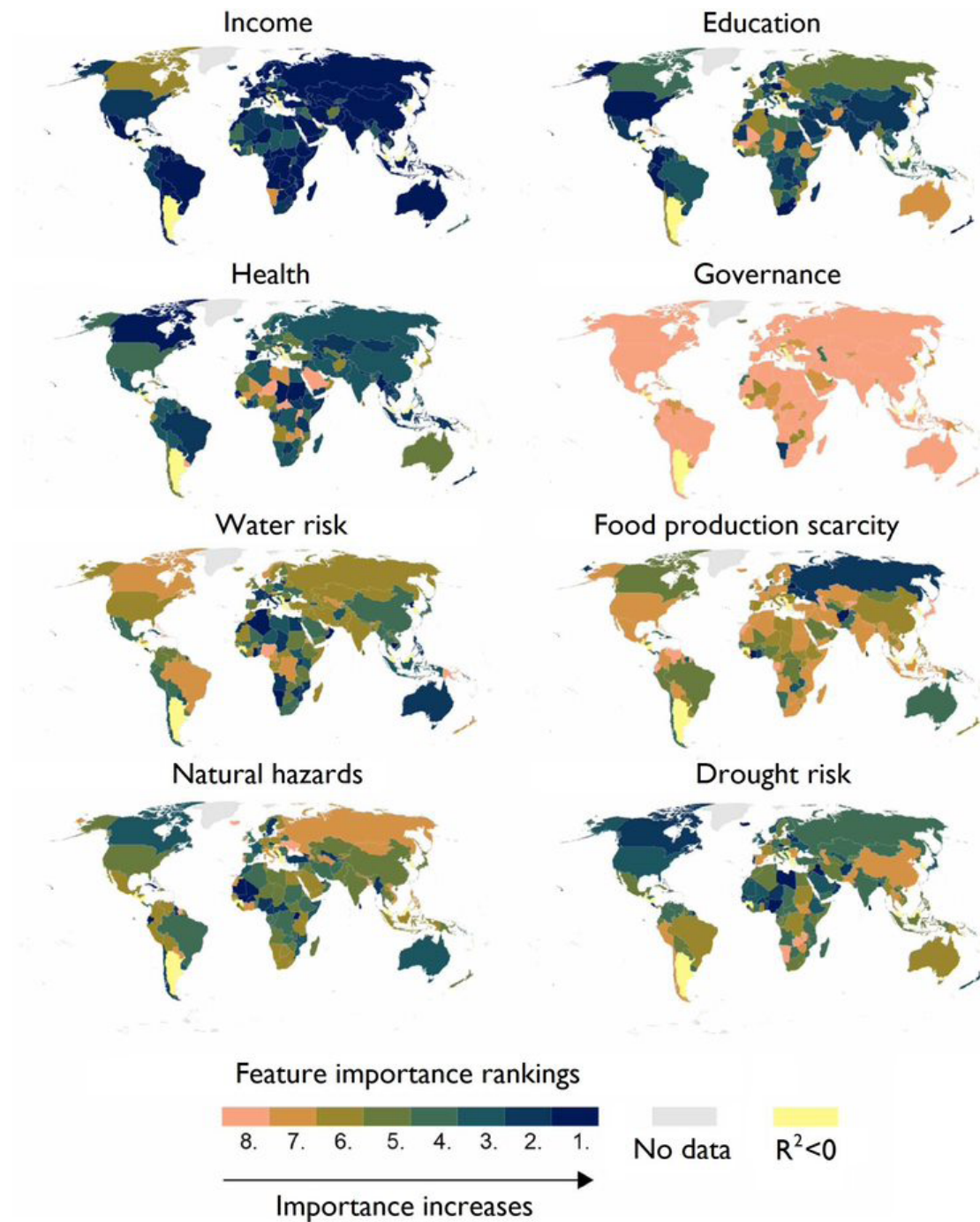

Source: Adapted from Schutte et al. (2021).

have played only a minor role compared to political violence.

Niva et al. (2021) applied a random forest model to explain migration patterns in a spatially explicit setting, providing a state-of-the-art quantification of how different drivers influence mobility to different extents in different parts of the world. The researchers modelled net migration over time (estimated from changes in local population sizes as well as birth and death rates) in every cell of a global grid as a function of local adaptive capacity – measured in terms of income, health, education, and governance – and environmental stress – measured in terms of natural hazards, drought risk, food insecurity, and water risk. The random forest approach allowed them to rank the relative importance of the various drivers of migration in different parts of the world, revealing the complex and spatially heterogeneous interplay of socio-economic and environmental factors in driving migration (Figure 4). In particular, income, education, and drought risk were found to be key drivers of out-migration from global areas characterised by high environmental stress.

The latest Groundswell report (Clement et al., 2021) provides a prominent example of a spatially explicit approach drawing on methods from econometric models. It quantifies the attractiveness of each cell of a spatial grid in terms of economic, demographic, and climate-change-related environmental conditions (water stress, crop yields, and sea level rise augmented by storm surge) and simulates the internal migration flows of people from less to more attractive locations. The analysis covers Sub-Saharan Africa, East Asia and the Pacific, Middle East and North Africa, Latin America, and Eastern Europe and Central Asia, with other regions omitted due to data limitations. Amongst the three approaches discussed in this section, the Groundswell model is the only one to project future mobility (section 6.1.10). To achieve this, it incorporates global projections of future economic and demographic developments under different socio-economic scenarios as well as projections of climate-change-driven changes in water stress, crop yields, and inundated land. The Africa Climate Mobility Model (Amakrane et al., 2023) uses a modified version of the Groundswell model for the special case of Africa and includes gradual ecosystem impacts, flood risks and conflict as additional driver variables.

Figure 4: Importance of different socio-economic and environmental factors on local out-migration. The higher the importance (ranking from 1 to 8) of a variable, the better it explains historical out-migration patterns in each country.

Source: Adapted from Niva et al. (2021).

6 | FUTURE PROJECTIONS

Existing quantitative projections of climate mobility in coming decades are based on the same two-step principle. First, statistical relationships between migration and economic, demographic, environmental, and other drivers are estimated based on historical data; second, the estimated relationships are applied to future projections of the drivers in order to infer future migration levels. Projections of many drivers relevant for mobility – ranging from per-capita income to heat wave exposure –, often at the sub-national level, have been generated for future scenarios under the standardised RCP-SSP framework (Text box 1).

Recent years have seen substantial progress on projecting human exposure to climatic hazards – including heat waves, droughts, wildfires, floods, storms, sea level rise, and crop failure – across different parts of the world and for different global warming scenarios (Pörtner et al., 2022; Lange et al., 2020). Appendix 1 provides a brief overview of important projections and data points. The quantity and quality of these biophysical projections far exceed those of the available projections of human responses to the hazards, in particular with regard to mobility. This is because climate risk assessments have largely been "privileging physical sciences over social science-informed understandings of local vulnerability and adaptive capacity" (Horton et al., 2021), resulting in top-down approaches that lack bottom-up insights related to local socio-economic contexts.

Progress on improving the evidence base on the likely mobility responses to projected climatic hazards has been slow, and quantitative projections of internal and international mobility in response to future climate change remain at a very early stage of development. The modelling landscape is patchy, with only a few approaches, based on different methodologies and assumptions, put forward thus far. The subsequent section discusses notable contributions.

Both the small number of existing forecasting models of climate mobility and the fact that they each examine slightly different research questions mean that it is not currently possible to conduct a systematic comparison of models, and assess uncertainties in the projections, in the manner that would be required for establishing scientific consensus. Projections from any one model must therefore be interpreted cautiously and should be seen as a starting point rather than a final product reliable enough to inform policy making – especially given the controversial nature of climate mobility forecasts in the past.

© International Organisation for Migration, 2020

TEXT BOX 1

Future socio-economic and climatic scenarios

To enable comparability across models simulating societal or environmental processes in coming years and decades, the research community has defined several plausible alternative future scenarios, each characterised by specific assumptions about the future trajectories of important variables. Forecasting models use these trajectories as inputs, allowing them to explore demographic, economic, social, environmental, and other implications associated with each of the different future scenarios. Two sets of scenarios are particularly relevant in the given context.

Shared Socioeconomic Pathways (SSPs) cover five alternative future demographic, economic, and social scenarios: 'Sustainability – Taking the Green Road (SSP1), 'Middle of the Road' (SSP2), 'Regional Rivalry – A Rocky Road' (SSP3), 'Inequality – A Road Divided' (SSP4), and 'Fossil-fuelled Development – Taking the Highway' (SSP5). The scenarios represent different assumptions about future population and economic growth, consumption patterns, international cooperation, and inequalities (see Riahi et al. (2017) for details). Representative Concentration Pathways (RCPs) cover several future scenarios of atmospheric greenhouse gas concentration, the key determinant of global warming. In recent years, RCPs have been integrated with the SSPs to create coupled future scenarios. For example, SSP1-RCP2.6 corresponds to an average global warming of ~1.9° by 2081–2100, relative to 1850–1900 levels, while SSP3-RCP7.0 corresponds to ~3.9° warming (Lee et al., 2021). Future global projections of environmental hazards relevant to human mobility, such as heat waves, droughts, flood risks, and crop failure, have been generated for these scenarios (Pörtner et al., 2022; Lange et al., 2020).

Figure 5: Global population under the five SSPs (left) and global mean surface air temperature changes under different SSP-RCPs (right)
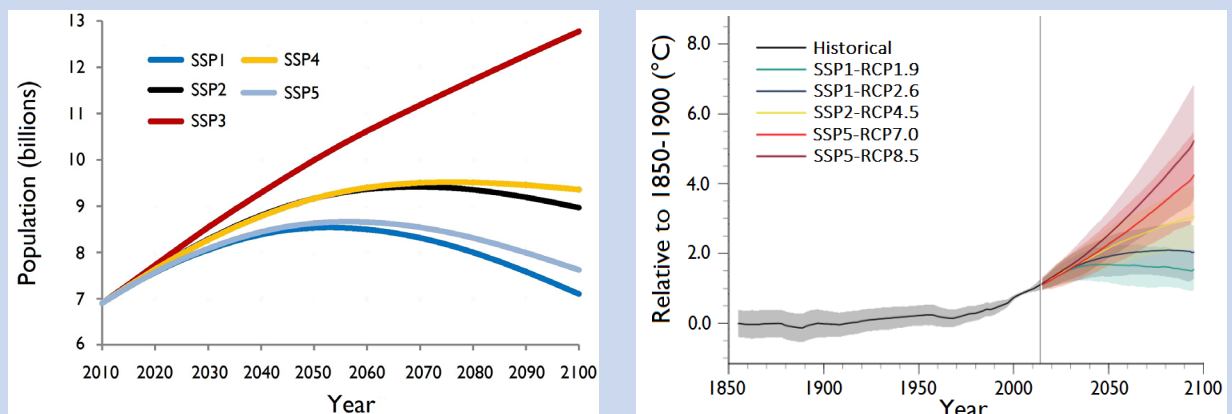
Source: Adapted from Samir and Lutz (2017) and Tebaldi et al. (2021).

Importantly, the SSP-RCP framework does not attempt to capture factors including future conflict, health crises, political, cultural, or technological changes that can have important short-to-long-term impacts on mobility. Mobility forecasting models based on SSP-RCP scenarios therefore also do not account for these factors.
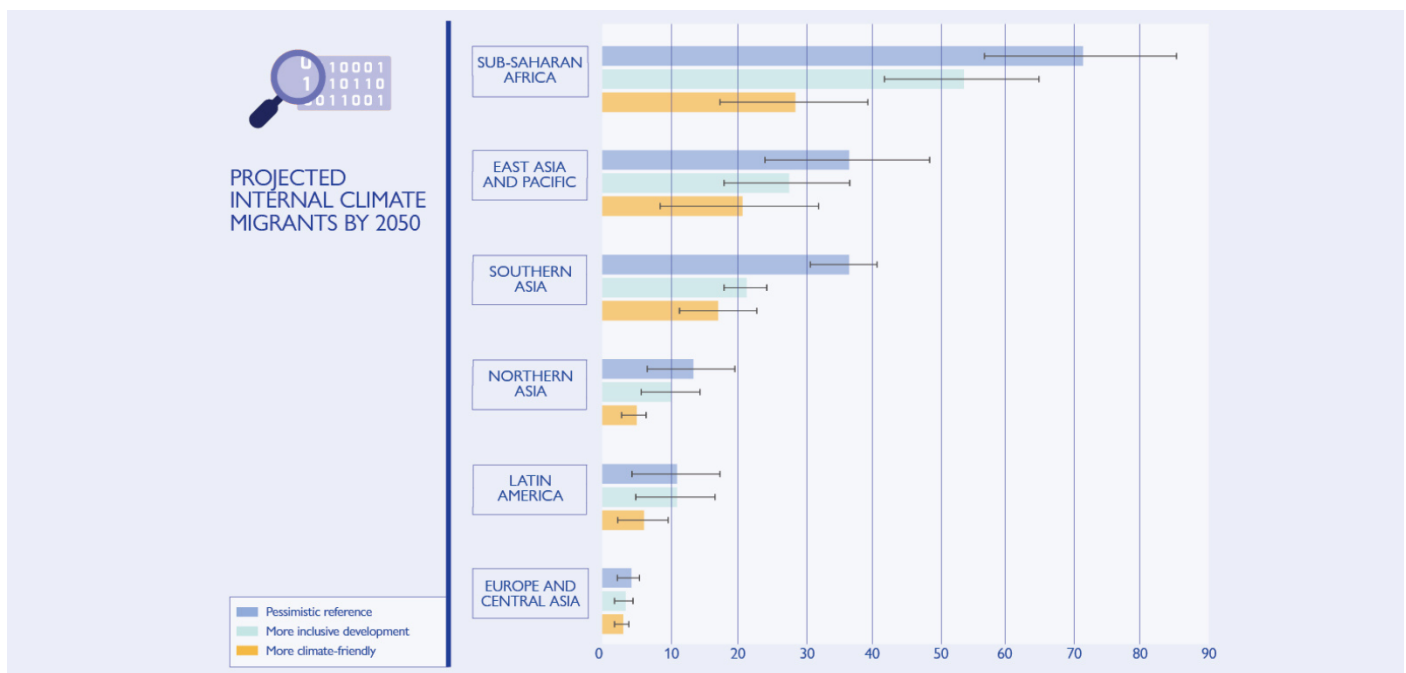
6.1.1. Internal mobility

The Groundswell model (Clement et al., 2021) provides projections of internal migration driven by climate change-induced slow-onset hazards until 2050 in six world regions. Estimates are available for three alternative future climatic and socio-economic scenarios, SSP4–RCP8.5 (termed "pessimistic" by the authors), SSP2–RCP8.5 ("more inclusive") and SSP4–RCP2.6 ("climate-friendly"). Climate change-induced internal migration by 2050 in the six regions is estimated at 44–113 million people under SSP4–RCP2.6, at 91–160 million people under SSP2–RCP8.5, and at 125–216 million under SSP4–RCP8.5. For each scenario, the ranges of the estimates are associated with uncertainties in the outputs of several alternative climate models included in the analysis. Baseline projections based on climate model ensemble averages suggest 78 million, 125 million, and 170 million internal migrants in the climate-friendly, more inclusive, and pessimistic scenario, respectively. A regional breakdown of the Groundswell projections is shown in Figure 6.

In any individual case, it is typically difficult to impossible to quantify the extent to which climate has impacted a person's decision or need to migrate (Boas et al., 2019; Obokata, Veronis, and McLeman, 2014). The Groundswell model – along with the models discussed in the following section – solved this problem by conducting future simulations with and without accounting for anthropogenic climate change. The number of migrants attributed to climate change was then defined as the difference between the climate-change and the counterfactual simulations.

Figure 6: Estimated climate-change-induced internal migration by 2050 by world region. Bars represent projections based on climate model ensemble averages; whiskers represent uncertainties across climate models.

Source: Own work based on data from Clement et al. (2021).

6.1.2. International mobility

A small number of econometric models has been used to project future global international migration flows for different socio-economic scenarios (e.g., Rikani and Schewe, 2021; Docquier, 2018; Cohen, 2012); however, these are too few to allow for a meaningful evaluation of consistency. Projective models at large spatial scales that additionally include climatic factors are even less developed. Benveniste, Oppenheimer, and Fleurbaey (2020) incorporated an econometric migration model into an Integrated Assessment Model (a complex modelling framework simulating major global environmental, economic, and social dynamics), in which remittance flows to migration origins are explicitly accounted for. The model suggests that climate change will marginally affect international migration, increasing global bilateral flows by ~75,000 people in 2100 compared to a no-climate-change scenario, assuming SSP2–RCP4.5 and current border policies. Earlier qualitative analyses support this conclusion that climate change is unlikely to induce large-scale cross-border, especially cross-continent, mobility (Borderon et al., 2019; Abel et al., 2019).

Somewhat higher numbers of climate-induced cross-border migration (though still small in comparison to internal movement) have been suggested by the Africa Climate Mobility Model (Amakrane et al., 2023), with estimates ranging between 400.000 and 500.000 international climate migrants in Africa alone under RCP6.0 by 2050 depending on the socio-economic scenario. Projected movement is particularly pronounced between countries of the Southern African Development Community.

Missirian and Schlenker (2017), focussing on forced migration, projected an additional 98,000 asylum applications in the EU alone by 2100 under RCP4.5, increasing to 660,000 under RCP8.5, based on a very simple relationship between temperature variations and asylum applications. Whilst the study received widespread media attention, it was quickly challenged by several rebuttal analyses questioning the statistical validity of the projections and arguing against large-scale climate-change-induced future asylum seeker inflow to Europe (Abel et al., 2019; Schutte et al., 2021).

Benveniste, Oppenheimer, and Fleurbaey (2022) examined the effects of climate change on resource-constrained international immobility, a topic that has traditionally received less attention than climate-induced displacement and migration but that has been brought into focus by the Foresight report (Black et al., 2011a) and several qualitative follow-up studies (Adams, 2016; Black et al., 2013; Findlay, 2011). Benveniste, Oppenheimer, and Fleurbaey

Figure 7: Estimated effect of climate change on the number of emigrants from the lowest-income quintile by 2100.
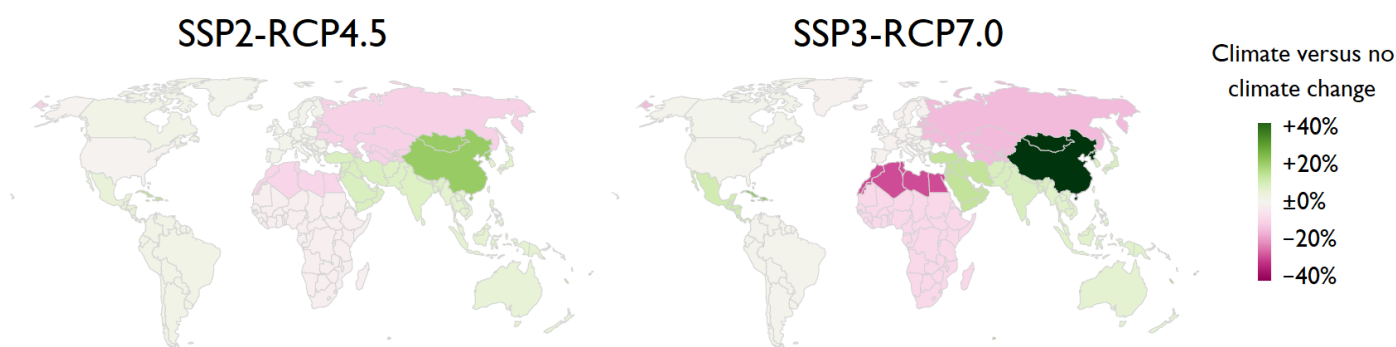
Source: Adapted from Benveniste, Oppenheimer, and Fleurbaey (2022).

(2022) examined global emigration at country level until 2100 for scenarios SSP2–RCP4.5 and SSP3–RCP7.0 as well as no-climate-change counterfactual, to project how climate change will affect the number of emigrants from a country's lowest-income quintile (i.e., the 20 poorest per cent of the population). They estimate this number to decrease in Sub-Saharan Africa, the former Soviet Union, and North Africa by two, ten and ten per cent, respectively, by the end of the century under SSP2–RCP4.5, and by nine, 14, and 28 per cent under SSP3–RCP7.0 demonstrating that resource-constrained immobility is likely to play an important role in the climate mobility nexus. In other parts of the world, notably in China, the opposite pattern is projected; in these cases, resource constraints are not too severe to dominate the pull factor towards higher-income locations.

© International Organisation for Migration, 2020

© International Organisation for Migration, 2019

7 | CONCLUSIONS AND RECOMMENDATIONS

Whilst several general statements on climate-related effects on global human mobility are supported by a majority of models developed since the late 2000s (section 5.1), there is overall no consensus about the quantitative effects of environmental factors on internal or international migration flows, with estimated mobility responses at times differing by orders of magnitude or even on the question whether they are positive or negative. In part, this is due to methodological limitations of existing models. Emerging next-generation models based on analytical methods tailored to the complexity of migration processes show that a deeper understanding can be gained. At present, however, these models are small in number and address slightly different questions, impeding comparisons that would allow researchers to separate robust trends from model uncertainties. Thus, quantitative results from climate mobility models are likely not yet at a point where they can reliably inform policy decisions related to future in- or out-migration that would be relevant for matters ranging from labour availability to regional development, from border policy to migrant protection and assistance.

We identify two priorities aimed to accelerate building consensus on the quantitative effect of climatic factors impact human mobility and on projecting plausible mobility futures.

Promote the development of models using state-of-the-art methods, combined with standardised modelling protocols

Accommodating the high complexity of migration processes necessitates going beyond classical econometric models of migration (Beyer, Schewe, and Abel, 2023). Recent examples of advanced machine-learning methods in climate mobility analyses, e.g., based on random forests, point the way towards the future of this research space.

Cutting-edge models will build on the substantial progress on projecting climate-related hazards made in recent years and combine these data with information on local socio-economic vulnerabilities and adaptive capacities. Disaggregated analyses that account for heterogeneities in mobility responses according to age, gender, education, and economic background will be particularly important (Beyer, Schewe, and Abel, 2023).

Developing standardised modelling protocols instead of addressing more or less different questions and contexts has greatly benefitted knowledge building in other disciplines (e.g., climate modelling (Eyring et al., 2016)). This approach would make it possible to rigorously assess agreement across model-based projections and quantify uncertainties.

Expand and improve mobility data

Even the best analytical models can only be as good as the historical data that they are trained on. Whilst the quantity and quality of global migration data have increased substantially over the past decade, much work remains to be done to improve the evidence base. State-of-the-art international flow data are available from 1990 but only in 5-year intervals (Abel and Cohen, 2022) (making it difficult to link migration flows with short-term exogenous events) and are subject to important uncertainties. Independent flow data have been collected by many national, supranational, and intergovernmental bodies, and could greatly enrich existing global datasets.

Available information on features including age, gender, education, and economic background of migrants is very sparse. Making disaggregated data available when they have already been recorded, or including them in future national data collection efforts, remains a high priority.

Most analytical studies on climatic impacts on migration have focussed on international migration (Hoffmann et al., 2020) even though environmental changes thus far have predominantly affected internal mobility. Expanding and curating datasets of internal migration – based on official monitoring (Bell et al., 2020), changes in spatial population distributions (De Sherbinin et al., 2015), or digital data sources (Tjaden, 2021) – will be crucial towards a better understanding of global patterns of climate mobility.

# PROJECTED FUTURE HUMAN EXPOSURE TO CLIMATE-RELATED HAZARDS

Progress on projecting future worldwide risks from climate-related hazards under different greenhouse gas concentration scenarios has been considerable (Pörtner et al., 2022), allowing for a spatially explicit mapping of human exposure to potential mobility-inducing conditions. This section provides a brief overview of important results for four hazard categories: heat stress, sea level rise, flooding, and agricultural yield decline.

8.1.1. Heat stress

Climate change is projected to significantly increase the intensity and frequency of heat waves across large parts of the world. Under the RCP2.6 and RCP4.5 scenarios, respectively, multi-model simulations suggest at least one additional extreme heat wave in 33 years in the United States, Europe, and large parts of Africa, and three waves in northern South America, some parts of Africa, the United States, and southern Europe in the near future (2020–2052) (Pörtner et al., 2022). More severe warming (RCP8.5) is projected to cause more than three extreme heat waves in 2020–2052 in large areas of the United States, South America, Europe, and Indonesia, and one extreme heat wave every two years in northern Brazil (Pörtner et al., 2022). By the end of the century (2068–2100), very large parts of the globe are projected to experience an extreme heat wave at least once every two years under RCP8.5 (Pörtner et al., 2022).

Figure 8: Number of extreme heat waves occurring in a 33-year interval under present and future climate. Median number of extreme heat waves of across multiple climate models in 1980-2012 (top row), 2020–2052 (middle row), and 2068–2100 (bottom row) for RCP2.6 (left column), RCP4.5 (centre column), and RCP8.5 (right column).
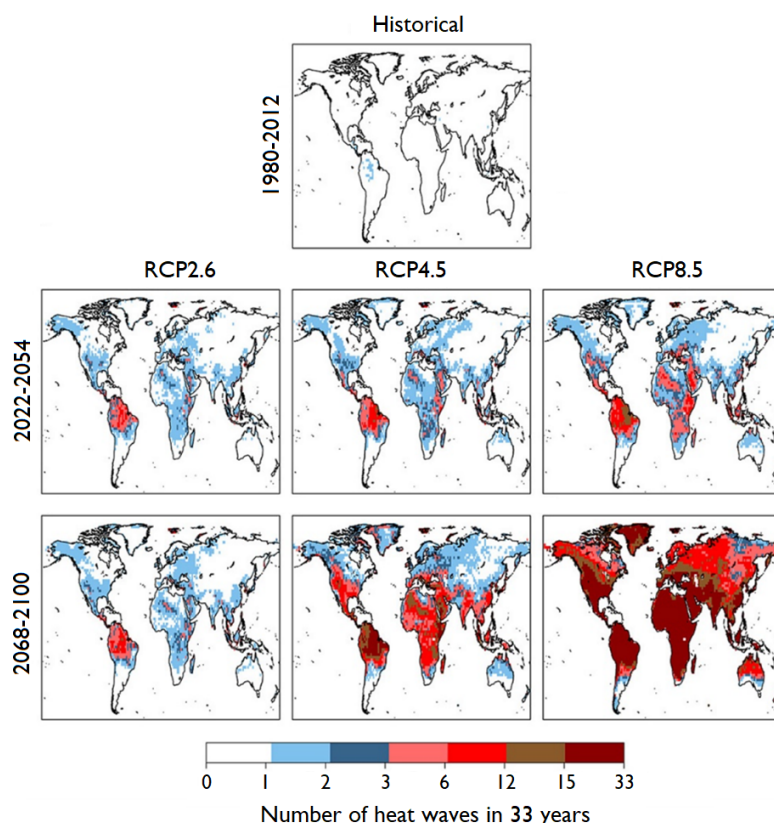
Source: Adapted from Russo et al. (2014).

Combined with projected steep increases in population densities in large parts of Sub-Saharan Africa, Central America, and South Asia in coming decades, these heat waves will affect large numbers of people. For RCP8.5, exposure to heat waves is projected to increase from currently 36 billion person-days to ~600 billion person-days in Asia, and from six billion person-days to ~700 billion person-days in Africa, by the end of the century (Liu et al., 2017). In North Africa and the Middle East, 300 million people are projected to be exposed to super- and ultra-extreme heat waves by the end of the century under RCP8.5, 90 per cent of which will reside in urban centres (Zittis et al., 2021). Potentially lethal heat thresholds will be exceeded on 50–150 days annually in west Africa at 1.6°C global warming, on 100–150 days in central Africa at 2.5°C, and on 200–300 days in tropical Africa for over 4°C global warming (Pörtner et al., 2022). South Asia is projected to experience more intense, more frequent, and longer heat waves; for example, at 1.5°C global warming, Kolkata will experience the heat equivalent to the 2015 record heat waves on an annual basis (Pörtner et al., 2022). In China's urban agglomerations, the number of heat danger days is estimated to increase from three days annually in the early 2000s to 8–67 days by the end of the century under RCP8.5, resulting in 310 million people facing more than three heat danger days annually. At 2°C global warming, half of the European population will face very high risk of heat stress in summer (Pörtner et al., 2022).

Figure 9: Frequencies of days exceeding 33°C wet-bulb temperature for different levels of increase in global surface average temperature. Sustained exposure to wet-bulb temperatures of this order is life-threatening even to healthy people.
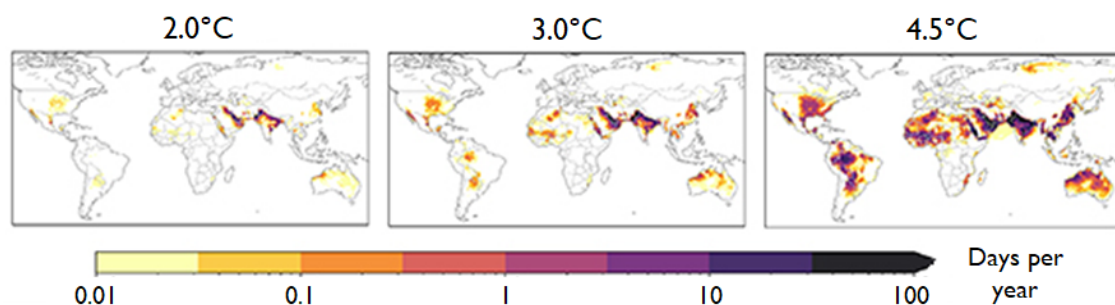
Source: Adapted from Li, Yuan, and Kopp (2020).

These expected increases in extreme heat will have significant effects on agricultural yields but also directly affect human labour capacity, behaviour, and physical and mental health (Xu et al., 2020), likely exceeding habitability thresholds across wide areas of the tropics and subtropics, especially in urban urban settings where heat-island effects occur (Pörtner et al., 2022). Migration to cooler climates may be the only viable strategy to avoid these impacts if in-situ adaptation measures are not available (Xu et al., 2020).

8.1.2. River floods

A warmer atmosphere holds more moisture, which, along with other factors, has been leading to an increase both in overall rainfall and in heavy precipitation events in many parts of the world, though, effects are spatially heterogeneous (Stott et al., 2016). These changes are expected to continue in coming decades and are projected to increase the frequency and magnitude of river floods in large parts of Asia, central Africa, western Europe, Central and South America, and eastern North America in coming decades (Pörtner et al., 2022) (Figure 10).

Figure 10: Multi-model median return period (in years) at the end of the 21st century (2071-2100) for river floods with a 100-year return period in the late 20th century (1970-2000).

SSP1-RCP2.6

SSP2-RCP4.5

SSP5-RCP8.5

Return period (years)

5   25   50   75   95   105   125   250   500   1000

Increased flood frequency ← | → Decreased flood frequency

High model agreement
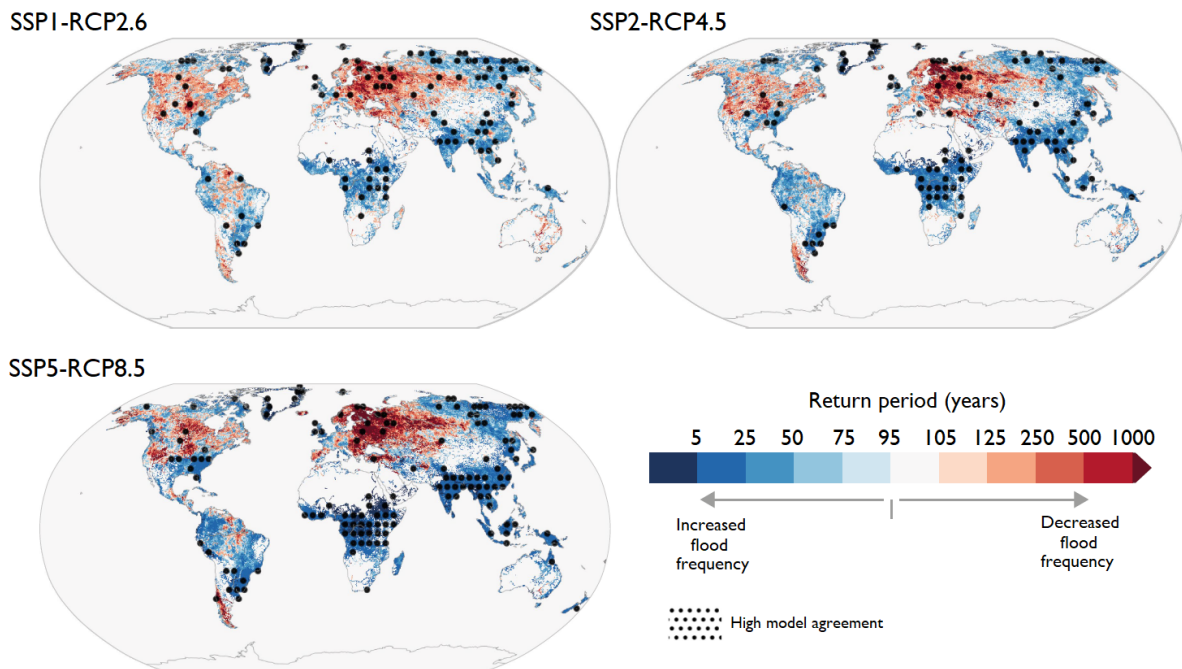
Source: Adapted from Pörtner et al. (2022).

These changes, combined with expected shifts in population densities, are expected to substantially increase the global population exposed to river floods. Across continents, higher levels of global warming are projected to increase exposure compared to historical levels (Pörtner et al., 2022). In particular, the population affected by river flooding is estimated to increase by 120 and 400 per cent for 2°C and 4°C warming, respectively, with worldwide flood-related fatalities expected to double (Pörtner et al., 2022). The highest number of people affected are projected for countries in South, East, and Southeast Asia.
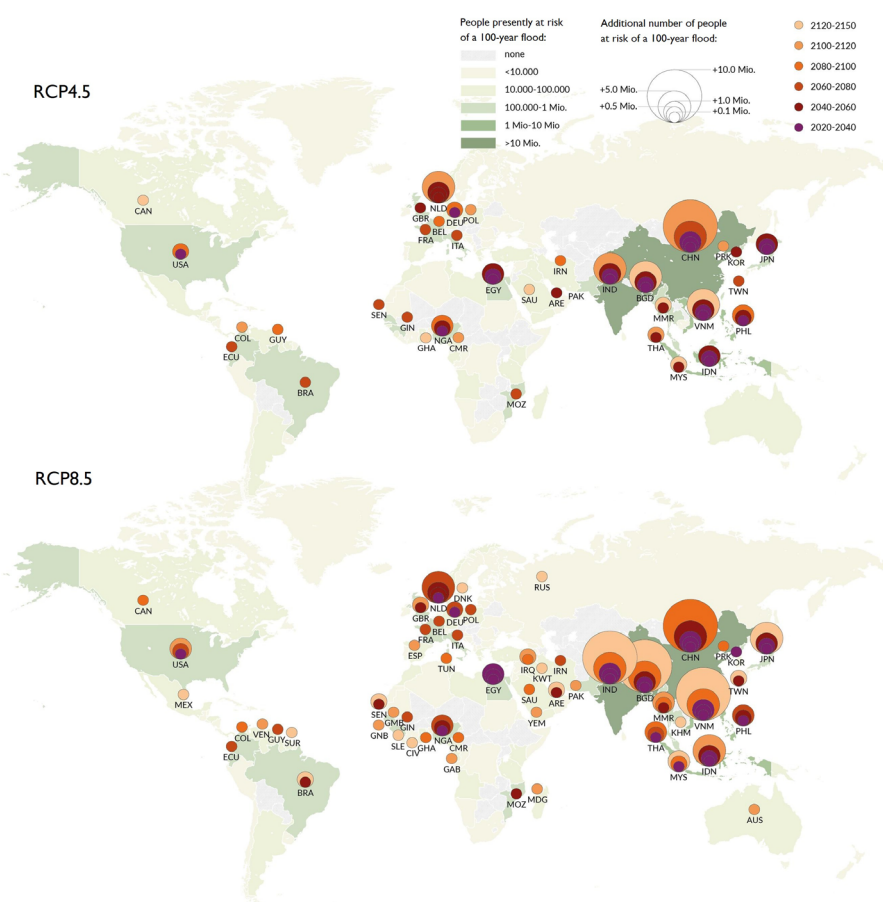
8.1.3. Sea level rise

Thermal expansion of ocean waters and melting of land-based ice sheets has been leading to a gradual and accelerating rise in sea level due to global warming over the past century. In addition to threatening direct inundation, this process increases coastal flood and storm hazards in many low-elevation areas across the globe, threatening human casualties, destruction of infrastructure, soil erosion, salinisation of freshwater sources, and agricultural losses. These risks are particularly concerning because population densities are significantly higher in coastal compared to non-coastal areas and are expected to further increase in coming decades. Most of the world's megacities are already located in coastal zones and river deltas, and urban areas are expanding faster in low-elevation coastal zones than anywhere else (Neumann et al., 2015).

Future projections of the number of people exposed to sea level rise differ first and foremost in how they define exposure. The most conservative definition refers to those living below future sea level with potential for permanent inundation. A series of projections estimates the population living in inundation zones at 110–130 million people for 1 metre global mean sea level rise, increasing to 410–430 million people for 6 metre sea level rise (McMichael et al., 2020) based on current population distributions and no adaptation efforts. Nicholls et al. (2011) considered the effect of dike and dune construction, estimating that the population threatened by inundation due to sea level rise of 0.5–2 metres could be reduced from 72–187 million to 41–305 thousand through appropriate adaptation.

Less conservative projections consider the number of people at risk of severe coastal flooding.

Figure 11: Present and projected future number of people at risk of 1-in-100-year coastal flood.

Source: Adapted from Haasnoot et al. (2021)

For example, Neumann et al. (2015) estimated the number of people living in 1-in-100-year coastal flood zones at 189 million in 2000 and 316–411 million in 2060, depending on future population growth. Figure 11 visualises current and projected future spatial heterogeneities in exposure to 1-in-100-year coastal floods for moderate and high global warming scenarios.

The least conservative estimates of exposure to sea level rise consider the global population living in low-elevation coastal zones or near-coastal zones, typically defined to be within a certain elevation and distance from the nearest coastlines.

For example, Merkens et al. (2016) and Jones and O'Neill (2016) overall consistently estimated the population living in low-elevation coastal zones in the year 2000 at 637 and 702 million, respectively, and project this number to increase to 830–1184 million and 493–1146 million, respectively, by 2100, depending on socio-economic developments. The number of people living within 2 metres of sea level is projected to increase from currently 267 million to 341–473 million for 1 metre sea level rise (Pörtner et al., 2022).

In terms of absolute numbers, Asia is expected to be impacted most severely by sea level rise, with 70 per cent of the global population expected to be exposed living in China, Bangladesh, India, Vietnam, Indonesia, Thailand, the Philippines and Japan (Pörtner et al., 2022). In the well-studied case of Bangladesh, in particular, 0.44 and 2 metres sea level rise are projected to cause the inundation of areas home to 0.73 and 2.1 million people, respectively, by 2100 (Pörtner et al., 2022).

Whilst comparatively small in absolute numbers, small islands are disproportionally impacted by sea level rise. Excluding Papua New Guinea, approximately 90 per cent of Pacific Islanders live within five kilometres of the coast, with most infrastructure being located within 500 metres of the ocean (Pörtner et al., 2022). A 5–10 centimetres additional sea level rise is expected to double flooding frequency in much of the Tropical Pacific and Indian Ocean. Under RCP8.5, some pacific atoll islands may undergo annual wave-driven flooding over their entire surface during the second half of the century (Pörtner et al., 2022).

8.1.4. Agricultural productivity

Altered temperature and precipitation patterns, elevated atmospheric carbon dioxide levels, and other factors linked to climate change are impacting global agricultural productivity worldwide. Due to the high complexity, nonlinearity, and context-specificity of these relationships, projections of future crop yields derived in the past decade have varied considerably, in some cases disagreeing even on the sign of the expected change (Rosenzweig et al., 2014; Jägermeyr et al., 2021).

According to the most recent multi-model simulations of the world's four major staple crops, yield levels of maize, the most important global crop in terms of total production, will be strongly negatively impacted, projected to decrease by 6 and 24 per cent under RCP2.6 and RCP8.5, respectively, by the end of the century compared to current levels (Jägermeyr et al., 2021) (Figure 12). In contrast, global wheat yields are projected to increase by 9 and 18 per cent under RCP2.6 and RCP8.5, respectively. Significant deviations from historical yield patterns are projected to emerge as early as the 2020s and 2030s. Projected global average yields in soybean and rice yields are expected to change less substantially, with no consistent sign emerging from alternative crop models (Jägermeyr et al., 2021). Importantly, these projections do not account for local adaptation measures, including switching to different varieties or crops, or changes in management and technology, which can increase yields substantially and at least partially compensate for adverse climatic changes.

Figure 12: Multi-model median changes in maize, wheat, soybean, and rice yields on present-day growing areas under RCP8.5 in 2069–2099 compared to current levels.
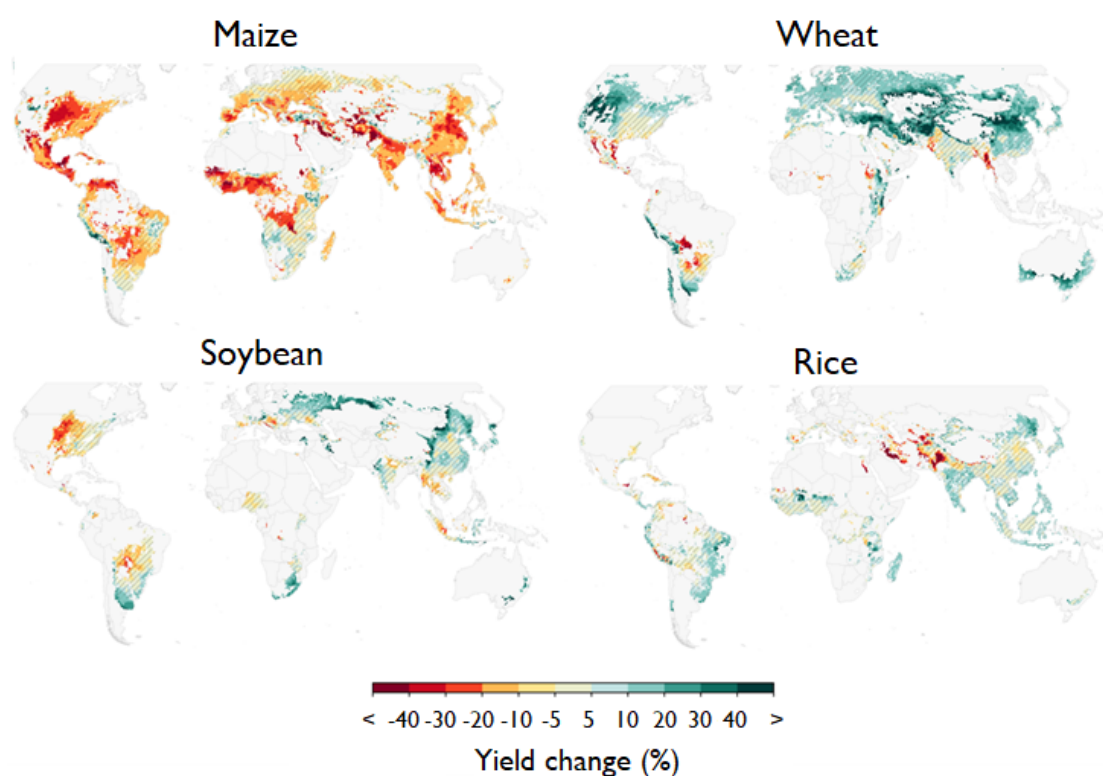
Source: Adapted from Jägermeyr et al. (2021).

Expected decreases in maize yields are comparatively homogeneous across space, with major declines expected in North America, Mexico, West Africa, Central Asia, and China. Projected yield changes for other crops are more spatially varied. Wheat yields are likely to decrease in Mexico, the southern United States, South America, and South Asia, but increase in the North China Plains, Australia, Central Asia, Middle East, the northern United States and Canada. Substantial yield declines are projected for soybean in the United States, Brazil, and Southeast Asia, and for rice in Central Asia (Jägermeyr et al., 2021).

For RCP6.0, yield losses linked to climate change have been projected to put an additional 8–80 million people, depending on socio-economic developments, at risk of hunger by 2050 (Pörtner et al., 2022). Regional disparities are high, with nearly 80 per cent of the population at risk of hunger projected to live in Africa and Asia (Pörtner et al., 2022).

Climate-change-induced fodder shortage, water stress, and heat also compromise livestock production, especially in Africa (Pörtner et al., 2022). Climate change impacts on oceans threaten catch potential of fisheries, with projections suggesting decreases in Africa of 3–41 per cent at 1.5°C global warming and 12–69 per cent at 4.3°C by 2081–2100, relative to 1986–2005 levels (Pörtner et al., 2022). Losses in marine fish catch potential may reach over 50 per cent by 2100 for nine out of 17 Pacific Island entities under both RCP2.6 and RCP8.5 (Pörtner et al., 2022).

Reductions in labour capacity induced by heat stress is projected to have significant effects on agricultural productivity. For example, in parts of South Asia, tropical sub-Saharan Africa and parts of Central and South America, the number of days with climatically stressful conditions for outdoor workers will increase by up to 250 workdays per year by the end of the century under RCP8.5–SSP5 (Pörtner et al., 2022).

REFERENCES

Abel GJ, Brottrager M, Cuaresma JC, et al.
2019 Climate, conflict and forced migration. Global environmental change. 54: pp.239–249
.

Abel GJ and Cohen JE.
2022 Bilateral international migration flow estimates updated and refined by sex. Scientific Data. 9(1): pp.1–11.

Adams H.
2016 Why populations persist: mobility, place attachment and climate change. Population and Environment. 37: pp.429–448.

Alessandrini A, Ghio D and Migali S.
2020 Estimating net migration at high spatial resolution. Publications Office of the European Union.

Amakrane K, Rosengaertner S, Simpson N, et al.
2023 African Shifts: The Africa Climate Mobility Report, Addressing Climate-Forced Migration & Displacement.

Barrios S, Bertinelli L and Strobl E.
2006 Climatic change and rural–urban migration: The case of sub-Saharan Africa. Journal of Urban Economics. 60(3): pp.357–371.

Beine M and Parsons CR.
2017 Climatic factors as determinants of international migration: Redux. CESifo Economic Studies. 63(4): pp.386–402.

Bell M, Bernard A, Charles-Edwards E, et al.
2020 Internal migration in the countries of asia. Springer.

Benveniste H, Oppenheimer M and Fleurbaey M.
2022 Climate change increases resource-constrained international immobility. Nature Climate Change. 12(7): pp.634–641.

Benveniste H, Oppenheimer M and Fleurbaey M.
2020 Effect of border policy on exposure and vulnerability to climate change. Proceedings of the National Academy of Sciences. 117(43): pp.26692–26702.

Berlemann M and Steinhardt MF.
2017 Climate change, natural disasters, and migration—a survey of the empirical evidence. CESifo Economic Studies. 63(4): pp.353–385.

Bettini G.
2017 Where next? Climate change, migration, and the (bio) politics of adaptation. Global Policy. 8: pp.33–39.

Beyer RM, Schewe J and Abel GJ.
2023 Modelling climate-induced migration: Dead ends and new avenues. forthcoming.

Beyer RM, Schewe J and Lotze-Campen H.
2022 Gravity models do not explain, and cannot predict, international migration dynamics. Humanities and Social Sciences Communications. 9(1): pp.1–10.

Biermann F and Boas I.
2010 Preparing for a warmer world: Towards a global governance system to protect climate refugees. Global environmental politics. 10(1): pp.60–88.

Black R, Adger WN, Arnell NW, et al.
2011a Migration and global environmental change: future challenges and opportunities.

Black R, Adger WN, Arnell NW, et al.
2011b The effect of environmental change on human migration. Global environmental change. 21: pp.S3–S11.

Black R, Arnell NW, Adger WN, et al.
2013 Migration, immobility and displacement outcomes following extreme events. Environmental Science & Policy. 27: pp.S32–S43.

Black R, Bennett SR, Thomas SM, et al.
2011 Migration as adaptation. Nature. 478(7370): pp.447–449.

Boas I.
2015 Climate migration and security: Securitisation as a strategy in climate change politics. Routledge.

Boas I, Farbotko C, Adams H, et al.
2019 Climate migration myths. Nature Climate Change. 9(12): pp.901–903.

Bohra-Mishra P, Oppenheimer M and Hsiang SM.
2014 Nonlinear permanent migration response to climatic variations but minimal response to disasters. Proceedings of the National Academy of Sciences. 111(27): pp.9780–9785.

Boote KJ, Jones JW, White JW, et al.
2013 Putting mechanisms into crop production models. Plant, cell & environment. 36(9): pp.1658–1672.

Borderon M, Sakdapolrak P, Muttarak R, et al.
2019 Migration influenced by environmental change in Africa. Demographic Research. 41: pp.491–544

Brown O.
2008 Migration and climate change. United Nations
.
Buhaug H, Nordkvelle J, Bernauer T, et al.
2014 One effect to rule them all? A comment on climate and conflict. Climatic Change. 127: pp.391–397.

Burke M, Hsiang SM and Miguel E.
2015 Climate and conflict. Annu. Rev. Econ. 7(1): pp.577–617.

Cai R, Feng S, Oppenheimer M, et al.
2016 Climate variability and international migration: The importance of the agricultural linkage. Journal of Environmental Economics and Management. 79: pp.135–151.

Cattaneo C, Beine M, Fröhlich CJ, et al.
2019 Human migration in the era of climate change. Review of Environmental Economics and Policy.

Cattaneo C and Bosetti V.
2017 Climate-induced international migration and conflicts. CESifo Economic Studies. 63(4): pp.500–528.

Cattaneo C and Peri G.
2016 The migration response to increasing temperatures. Journal of development economics. 122: pp.127–146.

Christian Aid.
2007 Human tide: the real migration crisis.

Clement V, Rigaud KK, de Sherbinin A, et al.
2021 Groundswell part 2: Acting on internal climate migration. World Bank.

Cohen J.
2012 Projection of net migration using a gravity model. In: Population Division, United Nations. New York. pp.1–8.

Coniglio ND and Pesce G.
2015 Climate variability and international migration: an empirical analysis. Environment and Development Economics. 20(4): pp.434–468.

De Sherbinin A, Levy M, Adamo S, et al.
2015 Global estimated net migration grids by decade: 1970–2000. NASA Socioeconomic Data and Applications Center (SEDAC) at http://sedac. ciesin. columbia. edu/data/set/popdynamics-global-est-net-migration-grids-1970-2000.

Docquier F.
2018 Long-term trends in international migration: Lessons from macroeconomic model. Economics and Business Review. 4(1): pp.3–15.

Elliott J, Müller C, Deryng D, et al.
2015 The global gridded crop model intercomparison: data and modeling protocols for phase 1 (v1. 0). Geoscientific Model Development. 8(2): pp.261–277.

Eyring V, Bony S, Meehl GA, et al.
2016 Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. Geoscientific Model Development. 9(5): pp.1937–1958.

Falco C, Galeotti M and Olper A.
2019 Climate change and migration: is agriculture the main channel? Global
    Environmental Change. 59: pp.101995.

Findlay AM.
2011 Migrant destinations in an era of environmental change. Global
    Environmental Change. 21: pp.S50–S58.

Gemenne F.
2011 Why the numbers don't add up: A review of estimates and predictions
    of people displaced by environmental changes. Global Environmental
    Change. 21: pp.S41–S49.

Ghimire R, Ferreira S and Dorfman JH.
2015 Flood-induced displacement and civil conflict. World Development. 66:
    pp.614–628.

Gleick PH.
2014 Water, drought, climate change, and conflict in Syria. Weather, climate,
    and society. 6(3): pp.331–340.

Güneralp B, Güneralp İ and Liu Y.
2015 Changing global patterns of urban exposure to flood and drought
    hazards. Global environmental change. 31: pp.217–225.

Haasnoot M, Winter G, Brown S, et al.
2021 Long-term sea-level rise necessitates a commitment to adaptation: A
    first order assessment. Climate Risk Management. 34: pp.100355.

Hausfather Z and Peters GP.
2020a Emissions–the 'business as usual' story is misleading. Nature.
    577(7792): pp.618–620.

Hausfather Z and Peters GP.
2020b RCP8. 5 is a problematic scenario for near-term emissions.
    Proceedings of the National Academy of Sciences. 117(45): pp.27791–
    27792.

Hoffmann R, Dimitrova A, Muttarak R, et al.
2020 A meta-analysis of country-level studies on environmental change and
    migration. Nature Climate Change. 10(10): pp.904–912.

Hoffmann R, Šedová B and Vinke K.
2021 Improving the evidence base: A methodological review of the
    quantitative climate migration literature. Global Environmental Change.
    71: pp.102367.

Horton RM, de Sherbinin A, Wrathall D, et al.
2021 Assessing human habitability and migration. Science. 372(6548):
    pp.1279–1283.

Hsiang SM and Burke M.
2014 Climate, conflict, and social stability: what does the evidence say? Climatic
change. 123: pp.39–55.

Hsiang SM, Burke M and Miguel E.
2013 Quantifying the influence of climate on human conflict. Science. 341(6151):
pp.1235367.

IDMC.
2023 Global Internal Displacement Database.

Jägermeyr J, Müller C, Ruane AC, et al.
2021 Climate impacts on global agriculture emerge earlier in new generation of
climate and crop models. Nature Food. 2(11): pp.873–885.

Jones B and O'Neill BC.
2016 Spatially explicit global population scenarios consistent with the Shared
Socioeconomic Pathways. Environmental Research Letters. 11(8): pp.084003.

Kaczan DJ and Orgill-Meyer J.
2020 The impact of climate change on migration: a synthesis of recent empirical
insights. Climatic Change. 158(3): pp.281–300.

Kelley CP, Mohtadi S, Cane MA, et al.
2015 Climate change in the Fertile Crescent and implications of the recent Syrian
drought. Proceedings of the national Academy of Sciences. 112(11): pp.3241–
3246.

Klepp S.
2017 Climate change and migration. In: Oxford research encyclopedia of climate
science.

L Perch-Nielsen S, B Bättig M and Imboden D.
2008 Exploring the link between climate change and migration. Climatic change. 91:
pp.375–393.

Lange S, Volkholz J, Geiger T, et al.
2020 Projecting exposure to extreme climate impact events across six event
categories and three spatial scales. Earth's Future. 8(12): pp.e2020EF001616.

Li D, Yuan J and Kopp RE.
2020 Escalating global exposure to compound heat-humidity extremes with warming.
Environmental Research Letters. 15(6): pp.064003.

Liu Z, Anderson B, Yan K, et al.
2017 Global and regional changes in exposure to extreme heat and the relative
contributions of climate and population change. Scientific Reports. 7(1):
pp.43909.

Marchiori L, Maystadt J-F and Schumacher I.
2012 The impact of weather anomalies on migration in sub-Saharan Africa. Journal of
Environmental Economics and Management. 63(3): pp.355–374.

Maurel M and Tuccio M.
2016 Climate instability, urbanisation and international migration. The Journal
      of Development Studies. 52(5): pp.735–752.

McMichael C, Dasgupta S, Ayeb-Karlsson S, et al.
2020 A review of estimating population exposure to sea-level rise and the
      relevance for migration. Environmental Research Letters. 15(12):
      pp.123005.

Merkens J-L, Reimann L, Hinkel J, et al.
2016 Gridded population projections for the coastal zone under the Shared
      Socioeconomic Pathways. Global and Planetary Change. 145: pp.57–66.

Missirian A and Schlenker W.
2017 Asylum applications respond to temperature fluctuations. Science.
      358(6370): pp.1610–1614.

Moore M and Wesselbaum D.
2022 Climatic factors as drivers of migration: a review. Environment,
      Development and Sustainability. : pp.1–21.

Müller C, Elliott J, Chryssanthacopoulos J, et al.
2017 Global gridded crop model evaluation: benchmarking, skills, deficiencies
      and implications. Geoscientific Model Development. 10(4): pp.1403–
      1422.

Myers N.
2002 Environmental refugees: a growing phenomenon of the 21st century.
      Philosophical Transactions of the Royal Society B: Biological Sciences.
      357(1420): pp.609–613.

Myers N and Kent J.
1995 Environmental exodus: an emergent crisis in the global arena. Climate
Inst.

Nawrotzki RJ and DeWaard J.
2018 Putting trapped populations into place: climate change and inter-district
      migration flows in Zambia. Regional environmental change. 18: pp.533–
      546.

Neumann B, Vafeidis AT, Zimmermann J, et al.
2015 Future coastal population growth and exposure to sea-level rise and
      coastal flooding-a global assessment. PloS one. 10(3): pp.e0118571.

New York Times and Lustgarten A.
2020 The great climate migration. New York Times Magazine.

Nicholls RJ, Marinova N, Lowe JA, et al.
2011 Sea-level rise and its possible impacts given a 'beyond 4 C world'in the
      twenty-first century. Philosophical transactions of the Royal Society A:
      mathematical, physical and engineering sciences. 369(1934): pp.161–
      181.

Niva V, Kallio M, Muttarak R, et al.
2021 Global migration is driven by the complex interplay between environmental and social factors. Environmental Research Letters. 16(11): pp.114019.

Obokata R, Veronis L and McLeman R.
2014 Empirical research on international environmental migration: a systematic review. Population and environment. 36(1): pp.111–135.

Omobowale AO, Akanle O, Falase OS, et al.
2019 Migration and environmental crises in Africa. Oxford University Press London.

Otto FE.
2017 Attribution of weather and climate events. Annual Review of Environment and Resources. 42: pp.627–646.

Peng B, Guan K, Tang J, et al.
2020 Towards a multiscale crop modelling framework for climate change adaptation assessment. Nature plants. 6(4): pp.338–348.

Peri G and Sasahara A.
2019 The impact of global warming on rural-Urban migrations: Evidence from global big data. National Bureau of Economic Research.

Pielke Jr R, Burgess MG and Ritchie J.
2022 Plausible 2005-2050 emissions scenarios project between 2 and 3 degrees C of warming by 2100. Environmental Research Letters.

Piguet E, Kaenzig R and Guélat J.
2018 The uneven geography of research on "environmental migration". Population and environment. 39: pp.357–383.

Piguet E, Pécoud A and De Guchteneire P.
2011 Migration and climate change: An overview. Refugee Survey Quarterly. 30(3): pp.1–23.

Pörtner H-O, Roberts DC, Adams H, et al.
2022 Climate change 2022: Impacts, adaptation and vulnerability. IPCC Geneva, Switzerland:

Ramos R.
2016 Gravity models: a tool for migration analysis. IZA World of Labor.

Rees P, Bell M, Kupiszewski M, et al.
2017 The impact of internal migration on population redistribution: An international comparison. Population, Space and Place. 23(6): pp.e2036.

Reuveny R and Moore WH.
2009 Does environmental degradation influence migration? Emigration to developed countries in the late 1980s and 1990s. Social Science Quarterly. 90(3): pp.461–479.

Rikani A, Otto C, Levermann A, et al.
2022 More people too poor to move: Divergent effects of climate change on global migration patterns. Environmental Research Letters.

Rikani A and Schewe J.
2021 Global bilateral migration projections accounting for diasporas, transit and return flows, and poverty constraints. Demographic Research. 45: pp.COV4–COV4.

Rosenzweig C, Elliott J, Deryng D, et al.
2014 Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. Proceedings of the national academy of sciences. 111(9): pp.3268–3273.

Russo S, Dosio A, Graversen RG, et al.
2014 Magnitude of extreme heat waves in present climate and their projection in a warming world. Journal of Geophysical Research: Atmospheres. 119(22): pp.12–500.

Salehyan I.
2008 From climate change to conflict? No consensus yet. Journal of peace research. 45(3): pp.315–326.

Schutte S, Vestby J, Carling J, et al.
2021 Climatic conditions are weak predictors of asylum migration. Nature communications. 12(1): pp.1–10.

Seneviratne S, Nicholls N, Easterling D, et al.
2012 Changes in climate extremes and their impacts on the natural physical environment.

Stern N and Stern NH.
2007 The economics of climate change: the Stern review. cambridge University press.

Stott P.
2016 How climate change affects extreme weather events. Science. 352(6293): pp.1517–1518.

Stott PA, Christidis N, Otto FE, et al.
2016 Attribution of extreme weather and climate-related events. Wiley Interdisciplinary Reviews: Climate Change. 7(1): pp.23–41.

Tjaden J.
2021 Measuring migration 2.0: a review of digital data sources. Comparative Migration Studies. 9(1): pp.59.

Warner K, Hamza M, Oliver-Smith A, et al.
2010 Climate change, environmental degradation and migration. Natural Hazards. 55: pp.689–715.

Wesselbaum D and Aburn A.
2019 Gone with the wind: International migration. Global and Planetary Change. 178: pp.96–109.

Xu C, Kohler TA, Lenton TM, et al.
2020 Future of the human climate niche. Proceedings of the National Academy of Sciences. 117(21): pp.11350–11355.

Zickgraf C.
2019 Climate change and migration crisis in Africa. The Oxford handbook of migration crises. : pp.347.

Zittis G, Hadjinicolaou P, Almazroui M, et al.
2021 Business-as-usual will lead to super and ultra-extreme heatwaves in the Middle East and North Africa. npj Climate and Atmospheric Science. 4(1): pp.20.