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Improving on Complexity: Ideas for Enhancing Quantitative Modeling of Climate Mobility

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Quantitative climate mobility research has, so far, focused primarily on climate change impacts on migration outcomes. This focus has led to a separation between quantitative climate migration research and the broader field of migration studies. In this paper ways are proposed for quantitative research to better address the complexity in the relationship between climate change and mobility. First technical suggestions are presented to improve upon migration model setups and designs and highlight promising developments. Then it is argued that quantitative methodologies can broaden the scope of research inquiries by examining how climate mitigation and adaptation efforts influence mobility, as well as assessing how mobility itself impacts vulnerability.

1. Introduction

In the last decade public, governmental, journalistic, and scholarly interest in the topic of climate-related migration has risen.[1,2] The increased focus is related to a variety of developments, including more frequent and intensive climate-related extreme weather events (e.g., the 2022 floods in Pakistan[3]), the importance of climate-related displacement for Loss and Damage negotiations,[4] attempts by political actors to use the threat of mass migration to push for various political agendas,[5–7] as well as contestation and militarization of existing immigration policies.[8,9] As a consequence, there are more and more quantitative scholars researching human mobility in a changing climate.[10] An influx of quantitative scholars offers new methods and additional conceptual understanding of human mobility and its relationship to climate variability and change. Here climate change refers not only to the changes within the natural earth system but also to the anthropological context (e.g. climate mitigation and adaptation efforts).[11,12] Furthermore, human mobility refers to a general definition covering all different forms of human movements such as rural-to-urban movements, international migration, seasonal relocation, etc.[13]

Climate change and mobility are themselves interrelated with many of the economic, social, and political processes that shape human life, making their relationship inherently complex. However, capturing this complexity through modeling presents significant challenges. Most quantitative literature studying human mobility has considered mobility primarily as a potential impact of climate change.[14] The focus has been on assembling causal chains, which can be intricate and influenced by a series of direct and indirect climate impacts on socioeconomic factors. These chains explain how biophysical climate events, such as droughts and floods, influence mobility. We refer to these methodologies as causal chain approaches.

Within this research framework, we find not only attribution studies[15] and work on causal inference,[16] but also scenario development and future projections.[17–19] These research approaches have profited from sophisticated modeling tools to disentangle some of the climate mobility dynamics, such as contextual effects (e.g., poverty, political marginalization, etc.)[1] and mechanisms.[20–22] Despite the methodological diversity, however, the questions remain focused on how climate variability, treated as a distinct factor, may or may not impact human mobility within the framework of a causal chain.

The emphasis on environmental factors as the dominant driver of mobility has led the climate migration literature to develop independently from migration studies.[23,24] For example, the recent "climate mobilities" agenda highlights the intricate relationships that migration has with relevant dimensions, such as demography, economy, history, culture etc., and how these relationships are influenced by climate change.[25,26] While such frameworks typically elude a rigid mathematical formulation, some scholars have tried to address this gap by integrating causal chains into migration system models.[17,27] While promising, this approach runs into several challenges due to e.g. poor data quality, deterministic modeling approaches, non-linear effects, and missing feedback relationships (see Section 2.1).

Even with better complex systems modeling, focusing on the effects of climate impacts on mobilities captures only a fraction of the intricate relationship between climate change and mobility, for two key reasons. First, climate change encompasses more

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than climate impacts or variability. Climate change influences mobility not only through direct biophysical effects such as sea level rise, drought, and extreme weather events, but also through the mitigation and adaptation measures humans undertake in response.[28] Second, mobility significantly influences both the exposure and vulnerability to climate impacts, as well as the effectiveness of mitigation and adaptation strategies.[28]

This paper contains a number of suggestions for how the quantitative literature on climate mobility can move forward and more effectively address the inherent complexity of the subject. Our approach is twofold. First, in Section 2.1 we propose several ways to incorporate further elements of complexity and interdependence that affect mobility. These technical proposals involve improved modeling techniques and deepening our understanding of uncertainty in climate mobility models. Second, as discussed in Section 2.2, we propose expanding the set of questions that quantitative researchers explore regarding climate mobilities. This involves expanding the notion of climate change in this body of literature to include adaptation and mitigation as well as exploring how mobility trends are reshaping the experiences of people and places with climate change. The ultimate goal is to enable quantitative tools to help create a more complex understanding of mobility under the conditions of climate change and to align quantitative climate mobility research with the broader debates about climate and mobility.

2. Ideas for Future Quantitative Climate Mobility Research

Within the climate-related human mobility literature, quantitative scholars have rarely referred to a particular theoretical framework when studying the topic.[10] While studies have most commonly explored whether climate factors affect human mobility and investigated the nature of, motivation for, or magnitude of the resultant movements, the underlying assumption was a causal chain connecting climate impacts to mobility outcomes. This approach has created conceptual and technical challenges that call for solutions within the realm of quantitative climate mobility research.[29]

In the following, we will highlight some fundamental challenges and discuss ideas on how to overcome them. We start with suggestions on improving modeling approaches and methodologies aiming at further representing complex relationships. These technical points are then followed by ideas on expanding the scope of climate mobility research.

2.1. Improve Complex Modeling

2.1.1. The Gravity Model

The gravity model is the most common statistical approach in quantitative (climate) migration studies.[30–35] The gravity model is a linear regression model,

$$M_{ij} \sim \frac{P_i^{\alpha} P_j^{\beta}}{d_{ij}^{\gamma}} \tag{1}$$

that borrows from Newton's Law of Gravity, where M_{ij} is the migration flow between location i and location j with population sizes P_i, P_j respectively, distance d_{ij}, and regression coefficients α, β, γ. Climate impacts enter either indirectly through the model variables or directly as additional factors in Equation (1). The gravity model has a number of issues that are illustrative of broader challenges in quantitative models of climate mobility.[36] For example, gravity models do not adjust for migration that has taken place and its effect on the population. So, if the value of the predictors stays the same year to year, the model will continue to predict the same amount of migration regardless of how many people have already migrated. In technical terms, this stems from the lack of a continuity equation.[37] Another issue is that the gravity model has no explicit mechanism to restrict migration flows to sensible values. Thus, it is possible to project more migration than the total population or negative migration flows.[38,39] Moreover, gravity models can "describe spatial patterns" in international migration quite well, but they do not capture changes in migration patterns over time.[34] This makes them ill- suited for future forecasting as well as causal identification. Finally, gravity models are dyadic in nature and ignore the influence of third countries on the migration flows between any two nations.

Some of the issues can be overcome by mathematically incorporating constraints. For example, gravity-type models cannot be used for extrapolation, but need to at least be combined with time evolution and mass flow conservation equations, e.g.

$$P_i(t_{j+1}) = P_i(t_j) * (1 + c_i(t_j)) - \sum_k \left[M_{ik}(t_j) \cdot (1 + c_i(t_j)) - M_{ki}(t_j) \cdot (1 + c_k(t_j)) \right] \tag{2}$$

where $c_i(t_j)$ is the natural population change rate in country i at time step t_j. The time evolution Equation (2) balances the migration flows and stocks by accounting for the natural population change (first addend), emigration flows (second addend) and immigration flows (third addend). These minimal examples already ensure a consistent representation and accounting of flows and stocks. Such equations are applied for gravity-type models[40] or in stochastic approaches.[41] Additionally, these equations add a new layer of complexity as migration feeds back into the other modeling components, e.g. population sizes.

To deal with migration flows outside the sensible migration rate interval [0,1] we recommend using non-linear extensions that decrease migration rates in limiting cases, e.g. ref. [40] employs an explicit migration shape factor

$$F(G) \sim \frac{1}{1 + \exp\left(-\gamma(G - G_0)\right)} \overset{G \to \pm\infty}{\longrightarrow} 0 \tag{3}$$

where G is the origin GDPc and $\gamma,\ G_0$ are parameters of the hump function. Such non-linear extensions not only increase the stability of the model but may also incorporate more complex migration mechanisms.

2.1.2. Data Challenges and Stochastic Approaches

Causal chain approaches run into empirical challenges when singling out climate drivers, mainly due to data quality and availability. International migration flows are estimates and they involve a large amount of uncertainty.[42] Even the subset of European countries that have the best available country-disaggregated bilateral migration flow data has been described as a "bronze standard". Adding error bars to these estimates can help, but in this case the upper and lower bars on an 80% confidence interval differ by a factor of 5.[43] Furthermore, data quality differs significantly across mobility types, with short-term disaster displacement data having particularly difficult data issues.[44] This makes any attempt to estimate individual parameters based on this type of data extremely fraught.[36] The problem is even more pronounced at the sub-national level – a major limitation given that similar climate impacts can have opposite mobility impacts depending on the regional context.[11,45,46]

Due to the large amount of uncertainty in mobility data and our understanding of the mechanisms driving it, it is generally better to use stochastic approaches to migration modeling than deterministic ones. Describing mobility as a stochastic process avoids the fallacy of Climate Determinism and Climate Reductionism[47] which is important because mobility is so deeply interwoven with all other social processes. Thus, we recommend adopting Bayesian[48,49] or stochastic evolution models[41] which are better suited for dealing with the biases in mobility data and the elusiveness of clear climate-mobility mechanisms. The Bayesian approach in ref. [49] is an auto-regressive model of order one (AR(1)). A minimal representation is

$$M_i(t_n) = \phi_i \cdot M_i(t_{n-1}) + \epsilon_i(t_n) \tag{4}$$

where $M_i(t_n)$ is the migration rate in country i at time step t_n, ϕ_i is the auto-regressive parameter for country i, and $\epsilon_i(t_n)$ is a normally distributed error parameter for country i at time step t_n. The model parameters are estimated through migration data which yields a data-driven approach with consequently weak assumptions on migration mechanisms. On the other hand, higher order models may be needed as diaspora effects and return migration stretch over longer time periods. Additionally, it is difficult to include interactions between migration and determinants of migration[50] in such model setups.

The stochastic evolution approach[41] is a dynamical model, where the native population P and migrant population D are connected via emigration M, assimilation/naturalization A and return migration R. The two main components are time evolution equations for P and D similar to Equation (2) and sampling from probability distributions to obtain M, A, and R. Knowledge on migration mechanisms is included through partitioning of the migration data that is used to estimate the probability distributions which is a different way to impose weak assumptions on the migration mechanisms. On the other hand, partitioning is limited by the resulting sample sizes that need to be sufficiently large to estimate probability density functions. A broad review of further modeling approaches is presented in ref. [51].

2.1.3. Complexity Theory

We emphasize the challenges of separating the effect of climate impact variables within a large complex system. This becomes obvious if we not only consider the direct impacts of climate extremes but also include the indirect impacts which are harder to identify. For example, given data availability, it may be possible to identify the impacts of an extreme weather event on short-term and localized displacement. However, the long-term climate-related implications (sea-level rise, climate mitigation measures, etc.) for mobility patterns are completely intertwined with the economic, social, and political aspects. Such indirect effects involve different regional and temporal scales of climate impacts, like drought worsening existing structural economic insecurity of local livelihoods,[52] that are difficult to estimate. They may also involve responses where climate mitigation and adaptation strategies generate mobility inequalities for affected populations,[53] and these effects may in fact be more important in shaping mobility.

Ideas from complexity science may be helpful to model interactions between mobility and the environment where a decoupling cannot be justified. This allows for the description of social tipping points, emergent phenomena[54] and critical phenomena which is beyond classical approaches. For example, network analysis has been applied in migration theory to look into migration patterns,[55–58] migrant remittances,[59] and social networks.[60] The basic idea of network analysis is to represent migration as a graph where each area/country represents a node and relationships like remittances or migration are modeled as edges. Such edges can be weighted and directional to account for different current strengths and flow orientations. Using concepts of graph theory, such as connectivity and clustering can help to understand underlying migration mechanisms and relationships. However, this is likely more feasible at a local scale using available data on migrant networks in a given region.

Wide-ranging complex relationship theories such as mobility transition theory,[61] world systems theory,[62] migration systems theory,[63] as well as other unifying perspectives,[64] are difficult to operationalize because they are not sufficiently formal in terms of the mathematical expressions applied. Promising mathematical approaches are network analysis to identify components/clusters in large complex world/migration systems.[65–70] After identifying such components or subsystems (a, b, c, …) and their relationship to each other, one can formalize these in terms of a coupled equation system, e.g.

$$\begin{aligned}
P_1(t_{n+1}) &= f_a(P_1(t_n), M^a_{1j}(t_n), \dots) \\
&\vdots \\
P_m(t_{n+1}) &= f_a(P_m(t_n), M^a_{mj}(t_n), \dots) \\
P_{m+1}(t_{n+1}) &= f_b(P_{m+1}(t_n), M^b_{m+1j}(t_n), \dots) \\
&\vdots
\end{aligned} \tag{5}$$

where each equation represents a time evolution (see Equation (2) for a simple example) with the difference being that the time evolution will differ between subsystem a, b, … represented by the functions f_a and f_b and the migration flows M_{ij}^a and M_{ij}^b from i to j. Subsystem a encompasses countries/areas indexed $1, \ldots, m$ while subsystem b is related to the indices $m+1, \ldots$. Another promising approach may be the application of agent-based models where the characteristics of each component are implemented as different agent groups.[20] Quantitative research can help here to formulate rigorous theories in a mathematically concise way and test them with observational data. In this context, theory development and enhancement can progress simultaneously through interdisciplinary collaborations. This approach is particularly vital because a significant portion of mobility knowledge is qualitative and not expressed in mathematical terms.

2.2. Expanding Research Questions

To better contribute to understanding mobility in the context of climate change, quantitative modelers can also broaden the scope of their inquiries. Climate adaptation, and especially climate mitigation, require large-scale transformations in the political economy of life on Earth. These changes are likely to significantly influence and be influenced by mobility patterns. Given that many of these changes such as a full-scale energy transition or the construction of low-carbon industrial processes are unprecedented, traditional causal inference techniques employed by quantitative modelers to identify causal chains between climate and mobility may fall short in addressing these new challenges. However, large-scale models of industrial, energy, and economic systems that guide the transition toward a net-zero world do exist. Quantitative modeling plays a crucial role in planning and carrying out climate mitigation efforts. Thus, many of our suggestions center around incorporating scenario modeling used for economic planning into the analysis of mobility.

2.2.1. Forecasting

During the past decade, researchers have produced a number of scholarly works as well as policy reports in which they forecast future mobility with respect to potential climate change scenarios.[17,27] Depending on the scenario, model, and data, we find results ranging from 10 million to 1 billion projected climate migrants.[71] This large discrepancy highlights the large differences in data usage, definitions of climate-related migrants, and climate-mobility mechanisms applied in the studies (see ref. [72] for an example). Most of the future climate scenarios used for these projections do not necessarily involve long-term effects such as conflict risk (for a notable exception see ref. [73]), or geopolitical rearrangements that are known to shift mobility patterns.[74] Forecasts and future scenarios operate not only with uncertainties of known mobility drivers but also the complexity to estimate the effect of known and unknown missing contributions.

Measures of uncertainty, such as confidence intervals and error bars, are, however, not only valuable for establishing the statistical significance of a particular conclusion. They can be instrumental in understanding the assumptions behind and model performances. Beyond their role in validation, understanding the (un)predictability of different mobility types can enable policy makers to focus on policies that can be scaled up or down as unexpected circumstances arise. For example, knowing that the uncertainty of short-term displacement predictions from an extreme weather event is significantly lower than that of long-term international migration forecasts, can lead to more effective planning. Uncertainty estimates also allow policymakers and researchers to investigate plausible upper-bound scenarios with higher mobility rates, necessitating more comprehensive planning.

2.2.2. Decision Making and Vulnerability

Mobility trends that are largely unrelated to climate change and variability will likely shape the different ways in which climate change is experienced. For example, the UN projects that 2.5 billion more people will live in cities by 2050,[75] hundreds of millions of Chinese people have moved toward the coast and toward cities,[76] millions of Southeast Asians moved abroad seeking work,[77] and Americans from the U.S. continue to move to the south and west.[78] None of these trends are climate driven, but all of them have important implications for the experience of climate change in both the sending and receiving societies.

Aside from a few studies showing that population growth is projected to be larger in more vulnerable areas[79] and that net migration to ecologically vulnerable areas varies by region,[80] we still know very little about the relationship between broader migration trends and climate change. One path forward would be to analyze whether current mobility trends are generally directing people toward or away from areas that are highly vulnerable to climate change. This could be done by combining recent mobility data with spatial measures of climate vulnerability. A follow-up analysis could leverage satellite imagery to assess whether these trends in population increases or decreases amplify or mitigate the exposure of the built environments to climatic hazards. For example, does urbanization typically involve development adjacent to the sea, thereby increasing exposure to rising sea levels? Conversely, do trends of depopulation in rural areas lead to the remaining population settling in locations less prone to flooding?

2.2.3. Mitigation, Adaptation, Habitability

A new concept within climate mobility studies is the notion of habitability.[81] It refers to the capacity for individuals to inhabit a particular area, extending beyond mere biophysical conditions for human life to include the social, economic, and political conditions essential for leading dignified lives in specific locales. Many of the factors that enhance a location's 'livability' such as access to water, food, and energy use, are currently being explored through scenario modeling of mitigation. For example, efforts have been made to model the energy requirements of countries in Sub-Saharan Africa within the framework of "universal energy access" literature.[82] Additionally, connections between water, food, and energy in improving irrigated agriculture have been explored,[83,84] and some studies extend beyond meeting mere basic needs to include the productive use of energy for manufacturing and industry.[85]

Despite the fact that mobility is partly motivated by the pursuit of dignified living conditions, models have not yet been extensively applied to examine the interplay between climate mitigation and mobility. We suggest utilizing scenarios from food, water, and energy system models to estimate long-term migration patterns. This approach involves defining habitability by determining if different plans ensure the minimum food, water, and energy consumption necessary for dignified lives. In the absence of these factors, at least some individuals will be forced to migrate to other areas. One major benefit of building migration projections around energy, food, and water system scenarios is that it eliminated the need to separate 'climate migration' from other forms of migration. Instead, we can integrate climate mitigation decision with other factors to generate comprehensive migration projections.

Similarly, we advocate for expanded analysis of the interactions between climate mitigation, mobility, and displacement. Specifically, we suggest merging large-scale land use models with different habitability assessments to predict displacement risks. Our central concern is that energy transitions could result in large-scale displacement and resettlement due to indicatives such as land-based carbon sequestration, increased mining or hydroelectric power generation.[86] Different Shared Socioeconomic Pathways (SSPs) and mitigation plans have implications for land use that vary significantly. Quantitative mobility scholars would be well-positioned to investigate the implications of these diverse scenarios for displacement and in mobility. By combining land use projection with a measure of the labor intensity of various activities (e.g. farming versus carbon sequestration), quantitative scholars can identify the displacement risks associated with specific mitigation policies. This area presents a critical opportunity for quantitative climate mobility scholarship to contribute to climate justice efforts, as control over land use remains a key cite of contestation between indigenous communities, governments, and international organizations.

Additionally, remittances from migrants play a crucial role in labor migration patterns and are considered one of the largest global anti-poverty programs.[87] Yet, in several critical regions, these patterns of migration and the financial remittances that migrants send back home are going to be completely rearranged by the energy transition. For example, well over 15% of global remittances are contributed by migrant workers[88] in the Persian Gulf, where economies are almost entirely dependent on oil. The large flow of migrants from Central Asia toward Russia, a country deeply reliant on fossil fuels for both exports and domestic production, exemplifies the broader trend of individuals gravitating toward oil-dependent economies.[89,90] Furthermore, the oil and gas industry is heavily dependent on migrant workers,[91] in ways that alternative energy sectors like solar, wind, and nuclear energy simply are not. Currently, quantitative scenario model such as integrated assessment models, are the main tools for anticipating and planning for future shifts in energy systems. Thus, the most promising way to understand how remittance flows will be affected by the energy transition would be to combine oil and gas consumption scenarios with economic models that evaluate the capacity of various countries to transition toward green production. This approach would provide a clear picture of which sectors in specific countries will be most affected. Combining this data with estimates of the number of migrants employed in each sector, even if rudimentary, or by making assumptions about the attractiveness of a places as a destination for migrants based on its economic situation, would offer insights into the various ways the energy transition might effect the existing labor mobility networks.

3. Conclusion

We have laid out a number of paths forward for different types of quantitative researchers to enhance their contribution to understanding the complexity of the relationships between climate change and mobility. Instead of proposing a singular, comprehensive model or framework, we suggest ideas that various research initiatives can adopt to enrich our understanding of mobility in a world facing climate change. One central thread that unites all of our suggestions is the recognition that climate change entails a transformation of the political, economic, and social systems that regulate human mobility.

In summary, we argue that the complexity of climate mobilities can be more effectively addressed by employing quantitative tools capable of managing uncertainties and interactions within the field, e.g. stochastic and complexity theory tools. Moreover, we emphasize the need to broaden the scope of research questions posed by quantitative researchers to include how climate adaptation and mitigation affect mobility as well as how mobility affects and shapes climate vulnerability.

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Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

All authors contributed to the conceptualization and writing of the manuscript.

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Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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