

Studying the Effects of Climate Factors on Forced Migration Models: The Case of South Sudan

Alireza Jahani¹, Diana Suleimanova¹, Maziar Ghorbani¹, and Derek Groen^{1,2}

¹ Department of Computer Science, Brunel University London, Uxbridge, UB8 3PH, UK

² Faculty of Science (Informatics Institute), University of Amsterdam, Science Park, 904 1098 XH, Amsterdam, Netherlands

{alireza.jahani,diana.suleimanova,maziar.ghorbani,derek.groen}@brunel.ac.uk

Abstract. The direct effects of climate variability on refugee mobility during conflict-driven displacement remain poorly quantified. This study investigates how precipitation and river discharge influence journey times and route accessibility within a multiscale agent-based simulation framework. Building on our earlier implementation, we analyse the integration of 40 years of ERA5 climate reanalysis data and corresponding GloFAS river-discharge records to derive evidence-based thresholds governing movement speed adjustments and route closures. Applied to the 2016–2017 conflict in South Sudan, the analysis demonstrates that while conflict drives departures, hydrological conditions regulate when, where, and how far displaced populations can travel by introducing seasonal slowdowns and route-level bottlenecks. Although climate coupling increases computational cost by a factor of 6.4, it reveals critical accessibility constraints that are not captured in performance-focused evaluations. Overall, this study provides a more detailed characterisation of climate-induced mobility constraints and enhances the interpretability of forced migration simulations.

Keywords: Forced Migration · Climate Variability · Agent-Based Modelling · Data Integration · South Sudan

1 Introduction

Forced displacement can be triggered by a range of factors, including conflict, environmental hazards, and economic crises, often forcing individuals to migrate in search of safety and stability [1]. Accurate forecasting of such movements enables humanitarian organisations and governments to plan resource allocation and improve emergency response effectiveness [2,3]. While previous displacement studies have largely focused on conflict and policy-driven mobility, there is a growing need to understand how environmental and climatic dynamics influence the accessibility of routes and the pace of migration.

In South Sudan, where only a small fraction of roads are paved and many routes are seasonally impassable, rainfall variability and flooding have a direct

impact on population movement [4]. During the wet season, journeys that take a few days in dry conditions can extend to several weeks or become entirely infeasible. Rainfall variability across the country ranges from 700–2,200 mm per year, with large deviations between the northern and southern regions [5]. These fluctuations have intensified in both frequency and magnitude due to global climate change [6], significantly altering accessibility and the timing of displacement events.

Our previous work [7] provided a technical overview of the multiscale agent-based framework for modelling forced migration, focusing on the coupling between macro- and microscale simulations and evaluating computational performance and validation accuracy. Building on that work, this paper examines a different aspect of the model by focusing on the role of climate factors in shaping displacement dynamics. Rather than analysing system performance, we provide a data-driven study of how precipitation and river discharge, derived from ECMWF ERA5 and GloFAS datasets, influence mobility within the simulation. In particular, we explain how these variables affect route accessibility, agent movement, and migration flows, and present updated results that give a clearer picture of climate–migration interactions. The main contribution of this study is threefold: (i) deriving hydrological thresholds based on long-term climate data, (ii) integrating these thresholds into agent movement rules, and (iii) analysing how climate conditions influence mobility patterns, including travel speed, route availability, and displacement timing.

This paper examines the 2016–2017 conflict in South Sudan as a case study to evaluate the impact of weather conditions on displacement patterns. Section 2 reviews related research on environmental migration and data-coupling approaches. Section 3 describes the integration of weather data into the multiscale framework and the adaptation of movement rules. Section 4 outlines the simulation design and data sources, followed by the results and discussion in Section 5. Finally, Section 6 concludes with reflections on model performance and directions for future work.

2 Background: Climate and Displacement

Agent-based simulation (ABS) has become an established approach for examining forced-displacement dynamics by modelling individual decision-making within social and physical environments [8,9,10]. Recent frameworks have demonstrated the ability to forecast displacement and support humanitarian planning by incorporating behavioural and demographic factors [11], while advances in platforms such as Flee 3 have improved modelling flexibility and realism [12]. But, prior work has focused primarily on sociopolitical drivers, such as conflict intensity and interventions, with less attention to environmental constraints like flooding or drought. Integrating such factors remains challenging, particularly in multiscale models requiring interaction between heterogeneous components [1,13]. Recent studies show that dynamic representations of physical environments can substantially affect route accessibility and simulation accuracy [14].

Climatic conditions are increasingly recognised as key modifiers of displacement patterns. Black et al. [15] identified rainfall variability, storms, and temperature rise as contributing factors to population movements, while Ahmed et al. [16] demonstrated correlations between refugee arrivals and regional weather anomalies. Recent empirical studies have further shown that extreme weather events can produce strong nonlinear increases in displacement, highlighting the sensitivity of mobility to environmental shocks [17]. At a broader scale, climate-induced stressors such as droughts, floods, and rising temperatures are projected to displace millions of people, particularly in vulnerable regions of the Global South [18]. Climate variability can also influence migration indirectly by shaping resource availability, migration flows, and conflict dynamics across African regions [19]. Nevertheless, direct empirical links between hydrological variables, such as precipitation intensity or river discharge, and the speed or route selection of refugees remain rare [20]. Most existing research examines how climate change influences conflict dynamics, rather than how climatic conditions affect displacement patterns and mobility once conflict-driven migration has begun. For example, Abel et al. [21] showed that lower precipitation levels increase the likelihood of conflict, indirectly contributing to displacement, while studies in the Sahel region highlight how environmental pressures exacerbate instability and migration risks [22]. Conceptual and methodological challenges further complicate the analysis of climate-induced displacement. Reviews of climate migration research emphasise uncertainties in defining displacement and distinguishing between environmental drivers and broader socio-political factors [23]. Moreover, recent assessments stress the importance of treating climate, conflict, and migration as interconnected components of a complex system, requiring integrated modelling approaches to capture their interactions effectively [24]. Simulation-based optimisation and decision-support approaches have also demonstrated the value of integrating environmental and logistical factors to improve humanitarian planning and resource allocation [25].

The underlying multiscale coupling mechanisms and baseline architecture used here were first introduced in [7]. While climate variability may not be the primary cause of displacement, it can substantially influence mobility pathways by altering route accessibility and travel conditions. However, these environmental constraints remain insufficiently represented in existing displacement models, which rarely account for their dynamic effects on movement after conflict-driven migration has begun. To address this gap, the present study builds on the existing multiscale framework to analyse how precipitation and river-discharge conditions affect route accessibility and travel times for refugees in South Sudan, providing a more detailed characterisation of climate-modulated mobility patterns within forced-displacement simulations.

3 Systematic Climate Data Integration Approach

The model is constructed following the Simulation Development Approach (SDA) introduced by Suleimenova et al. [26]. This structured workflow supports the

stepwise creation, calibration, and validation of agent-based simulations of forced displacement. Conflict events and population data are obtained from the Armed Conflict Location and Event Data Project (ACLED) [27] and UNHCR statistics, while road networks and settlement coordinates are retrieved from OpenStreetMap. These inputs are identical in structure to those used in the earlier framework. The underlying implementation of the SDA for multiscale coupling was previously detailed in our ICCS 2021 paper [7]. The present study complements our 2021 work by addressing the same modelling problem while focusing on different aspects of its implementation. Specifically, we provide a detailed account of the algorithmic structure and integration of dynamic precipitation and river discharge data, clarifying their role in shaping migration dynamics within the Flee framework.

3.1 Climate Data Processing and Coupling

Weather and hydrological information were incorporated through an acyclic (one-way) coupling with ECMWF ERA5 reanalysis and Global Flood Awareness System (GloFAS) datasets, accessed via the Copernicus Climate Data Store. This integration improves the physical realism of the simulation by allowing route accessibility and agent speed to vary dynamically with daily climatic conditions. Full details of the data extraction and preprocessing workflow are provided in our previous study [7].

To derive representative precipitation thresholds, forty years of ERA5 data were analysed to capture rainfall variability across South Sudan. Data for the simulation period (1 June 2016–31 July 2017) were aggregated to daily totals and processed for regional parameterisation, with separate datasets for the Upper Nile, Jonglei, and Gambela regions to reflect spatial heterogeneity. ERA5 precipitation data were used at a spatial resolution of $0.25^\circ \times 0.25^\circ$ over $4.5\text{--}11.75^\circ$ N and $29.5\text{--}35.25^\circ$ E [28], including the number of rainy days per month (N) and total precipitation (tp). Hydrological data were obtained from the GloFAS reanalysis [29], providing daily discharge rates for the same domain, along with 2-, 5-, and 20-year return-period discharge values for the White Nile basin.

Together, these datasets form the climate-coupling layer of the simulation. During runtime, precipitation and discharge thresholds dynamically adjust agent speed and route accessibility, enabling the model to capture seasonal flooding effects on movement. Figure 1 shows the updated agent decision-making flowchart in the Flee framework, illustrating how the multiscale context from [7] is implemented and how climatic variables are integrated into movement decisions. Unlike our earlier work, which focused on the coupling architecture, this study examines the behavioural implications, analysing how climate-driven constraints shape agent mobility and emergent displacement patterns.

4 Evidence-Based Climate Impact Rules

South Sudan has a tropical climate with a wet season extending roughly from March to October and a dry season from November to February. Annual rain-

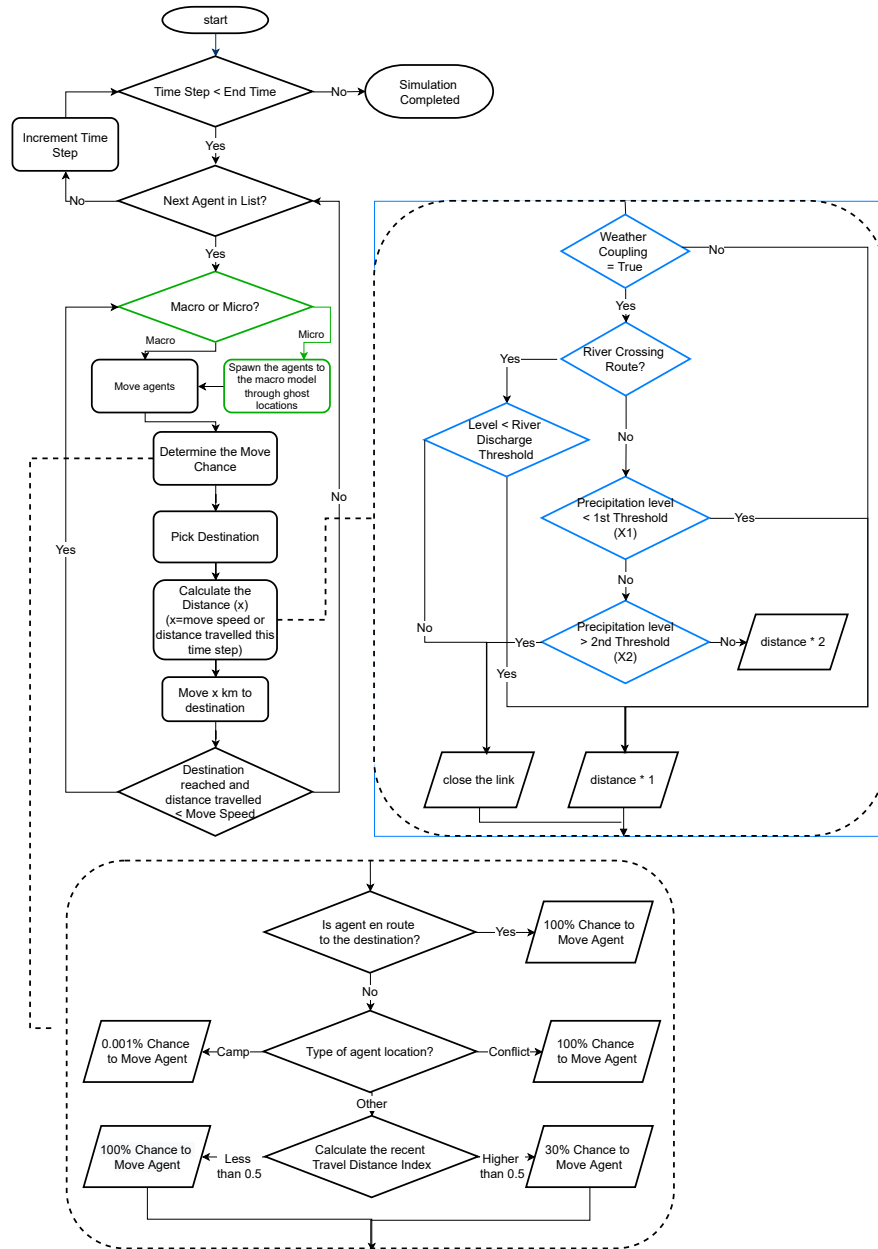


Fig. 1: Overview of the agent decision-making algorithm in Flee, incorporating the multiscale context [7] as well as the river discharge and precipitation components.

fall ranges from 700–1,300 mm in the northern regions to 1,200–2,200 mm in the southern uplands, with most precipitation occurring during the wet season. Flooding, particularly between July and September, constitutes the country’s most severe natural hazard. Intense rainfall frequently causes the Nile and its tributaries to overflow, disrupting transportation and displacing local populations. According to the United Nations Office for the Coordination of Humanitarian Affairs (OCHA), about 625,000 people were affected by flooding along the White Nile between July and September 2020. This context underscores the relevance of analysing how precipitation and river discharge influence refugee mobility and accessibility, forming the empirical basis for integrating climate dynamics into displacement simulations.

To parameterise the hydrological component of the movement algorithm, we analysed historical river-discharge records from GloFAS. Hourly discharge data along the White Nile revealed substantial variability between typical rainy-season conditions, such as September 2016, and major flood episodes, such as September 2020, during which average flow rates tripled at several monitoring locations. These observations informed the calibration of the movement rules used in the climate-coupled simulation.

4.1 Precipitation-Based Thresholds

Two statistical thresholds, X_1 and X_2 , were derived from forty years of ERA5 precipitation data to capture the relationship between rainfall intensity and mobility constraints. When total precipitation at a given location is below 15% of its long-term mean ($tp < X_1$), agent speed remains unchanged, representing normal travel conditions. For moderate rainfall, where precipitation lies between 15% and 75% of the average ($X_1 \leq tp < X_2$), agents experience reduced mobility by doubling the effective route distance, thereby halving their speed. When precipitation exceeds 75% of the mean ($tp \geq X_2$), the corresponding route is treated as impassable and temporarily closed. This rule set, illustrated schematically in Figure 1, captures the nonlinear relationship between rainfall intensity and mobility.

4.2 River-Discharge Threshold

A discharge threshold of 8,000 m³/s was established for the White Nile based on long-term GloFAS reanalysis records. When simulated river discharge at a route midpoint exceeds this threshold, the corresponding connection is deactivated to represent the flooding of crossings or low-lying roads. Historical analysis indicates that during major flood years, discharge values can surpass the multi-year mean by a factor of three, consistent with field observations and satellite-derived flood extents. This empirical threshold ensures that the model captures the hydrological constraints that strongly influence accessibility during extreme flood events.

4.3 Operational Coupling Workflow

The climate-coupling routine operates through both pre-processing and runtime integration between the processed ERA5 and GloFAS datasets and the multiscale migration model. Following the data-processing pipeline outlined in Section 3, daily precipitation and discharge values are interpolated to the midpoints of each route segment and stored as structured input files. During each simulation time step, the model dynamically retrieves these values to evaluate local environmental conditions. Based on the predefined precipitation and discharge thresholds, agent speed is adjusted or affected links are temporarily deactivated, embedding environmental feedback into route selection. Unlike our earlier coupling study [7], which focused primarily on system-level inter-model communication, the present study does not introduce new algorithmic components but instead analyses agent-level logs to provide a more detailed examination of how climatic conditions shape simulated mobility patterns.

5 Results and Discussion

The present study revisits the multiscale agent-based simulation framework introduced in our previous work [7], implemented using the Flee toolkit [26], and examines it from a different analytical perspective. The earlier study focused on validation error, execution time, and coupling overhead, showing that the multiscale framework reduced validation error by approximately 31% compared to a single-scale baseline while maintaining similar computational cost. Although the inclusion of precipitation and discharge coupling had limited impact on validation accuracy, it increased runtime due to the processing of time-varying climatic inputs. A detailed breakdown of these performance metrics, including both file-based and MUSCLE3-based coupling modes, is provided in [7]. In contrast, the current study shifts the focus from performance evaluation to behavioural and environmental dynamics, examining how route accessibility and agent speed vary with precipitation and river-discharge conditions, and analysing the implications of these climate-driven constraints on mobility patterns.

5.1 Climatic Variability and Mobility Patterns

To examine how climatic variability shapes population mobility, we analysed correlations between daily precipitation intensity and several displacement indicators generated by the simulation. These plots link precipitation with newly displaced populations, active movers, and mean travel distances, showing how rainfall fluctuations influence both the initiation and persistence of displacement behaviour.

Figure 2 illustrates the relationship between average daily precipitation and the number of newly displaced individuals. Each point represents a single day, with colour indicating temporal progression and the dashed line showing the fitted linear trend. The results show substantial variability at low precipitation

levels, where both small and large displacement events occur, while higher precipitation is associated with a slight decline in displacement. This suggests that although rainfall may coincide with displacement events, increased precipitation constrains mobility by reducing route accessibility, highlighting the nonlinear influence of rainfall on displacement dynamics.

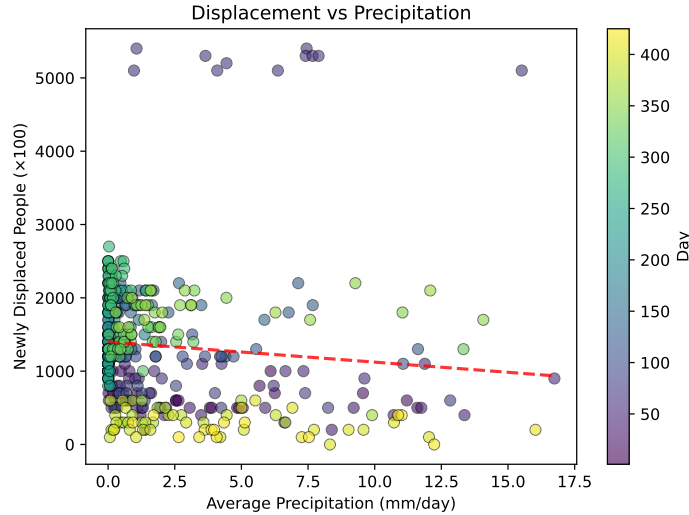


Fig. 2: Comparative correlations between average daily precipitation and newly displaced population.

Figure 3 shows the relationship between average daily precipitation and the number of active movers in the simulation, expressed in people-equivalent units (1 agent = 100 people). Each point represents a single simulation day, linking rainfall intensity to the size of the population in transit within the total simulated population of 567,100 people. High mobility occurs mainly under low to moderate precipitation, while heavier rainfall is associated with reduced and fragmented movement levels, indicating that increased precipitation constrains continued travel by limiting route accessibility.

Figure 4 shows the relationship between average daily precipitation and the mean distance travelled by agents in the simulation. Each point represents a single day, linking rainfall intensity to average mobility. Longer travel distances occur mainly under low to moderate precipitation, while heavier rainfall is associated with shorter distances, indicating that increased precipitation constrains movement by reducing travel speeds and route accessibility.

Figure 5 presents a temporal comparison of newly displaced populations and average daily precipitation using a dual-axis time series. The overall correlation is weak (correlation coefficient = -0.100), indicating that rainfall alone is not a strong linear predictor of displacement magnitude, which is expected given

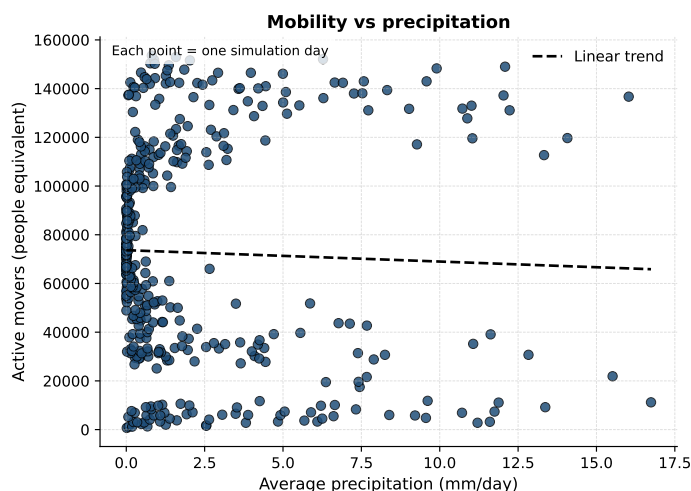


Fig. 3: Relationship between average precipitation and active movers (people-equivalent; 1 agent = 100 people). Each point represents one simulation day within the total population of 567,100 people.

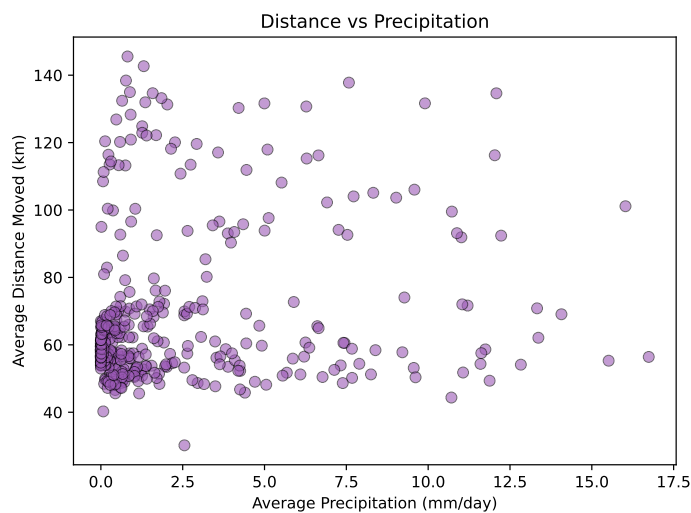


Fig. 4: Comparative correlations between average daily precipitation and average travel distance.

that conflict remains the primary driver. Despite this, a clear seasonal pattern emerges: displacement increases during drier periods when routes are accessible and declines during wetter periods as rainfall and flooding constrain mobility. This highlights an important distinction: precipitation does not directly trigger

displacement but modulates when and how movement occurs by affecting route accessibility. The weak correlation therefore reflects the nonlinear and indirect role of climate factors, which act as constraints on mobility rather than primary drivers, shaping displacement through threshold effects and accessibility limitations rather than simple linear relationships.

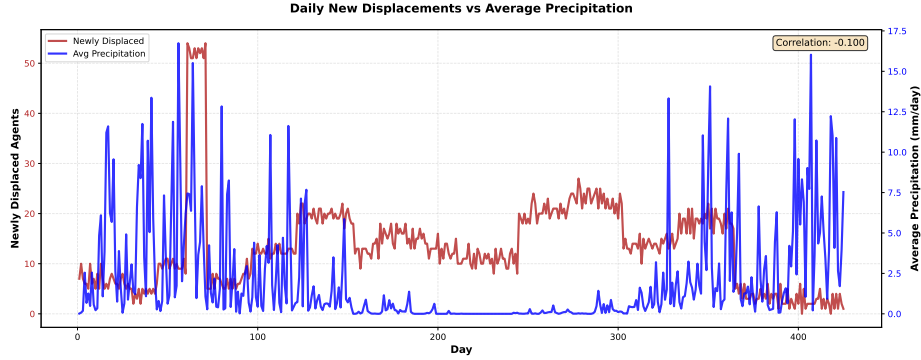


Fig. 5: Temporal comparison of newly displaced population and average precipitation (dual-axis plot). Synchronised peaks indicate the strong influence of rainfall intensity on displacement magnitude.

Figure 6 presents a daily comparison of river discharge and displacement along the Tonga–Malakal corridor, showing an inverse relationship between river flow and crossings. During periods of high discharge, few crossings occur due to limited accessibility, while declining water levels correspond to increased movement as routes become passable. Overall, the figure demonstrates that river discharge acts as a temporary environmental constraint, shaping the timing and pathways of conflict-driven displacement.

5.2 Discussion

The findings indicate that climatic variability influences forced displacement by regulating mobility rather than directly initiating departures. While conflict remains the primary driver of displacement onset, precipitation and river discharge shape how movement unfolds by affecting route accessibility and travel speeds. These effects are nonlinear: moderate rainfall allows continued, though slower, movement, whereas intense precipitation or high discharge can fragment the transport network through temporary link closures. Climate therefore acts less as a trigger and more as a regulator of the timing, direction, and speed of displacement, factors that are critical for humanitarian forecasting and response planning.

Synthesising the cross-figure analyses, three climate-modulated mobility regimes emerge (Table 1). Under dry conditions, low precipitation and discharge main-

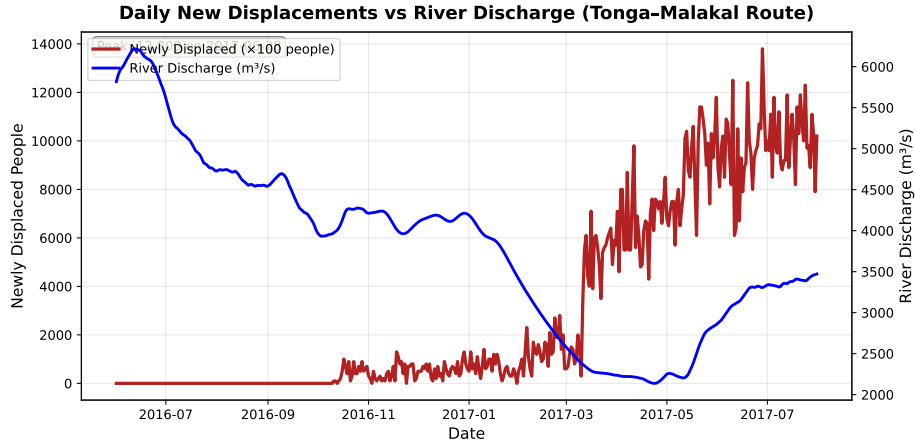


Fig. 6: Daily newly displaced population and river discharge levels along the Tonga–Malakal route (dual-axis plot), illustrating the association between river discharge and cross-river mobility.

tain high network connectivity, enabling higher departure rates, longer travel distances, and sustained flows. In moderately wet conditions, movement slows but remains largely continuous. In contrast, extreme wet conditions—characterised by heavy rainfall and/or high discharge—lead to route fragmentation, corridor closures, and constrained accessibility, resulting in disrupted movement, reduced departures, and delayed arrivals. Framing these dynamics as regimes, rather than linear relationships, highlights threshold effects and structural transitions that are important for anticipating when displacement may accelerate, slow down, or temporarily stall.

Table 1: Climate-modulated mobility regimes identified in the simulation.

Regime	Climatic State	Mobility Response	System Effect
Dry	Low precipitation Low river discharge	High departure rates Long-distance travel Sustained flows	Rapid spatial expansion
Moderate Wet	Moderate rainfall	Reduced travel speeds Continued connectivity	Delayed but ongoing displacement
Extreme Wet	Heavy precipitation Elevated river discharge	Link closures Route fragmentation Constrained accessibility	Bottlenecks Delayed arrivals

These regime dynamics are observable at both seasonal and corridor scales. Temporally, displacement intensifies during drier periods when routes remain

accessible, suggesting predictable windows of accelerated arrivals at destination sites. Conversely, wet-season conditions are associated with slower flows and potential accumulation of populations along partially blocked corridors. Although acute conflict events may generate short-lived surges during heavy rainfall, such spikes are rarely sustained when environmental barriers persist. Spatially, the Tonga–Malakal corridor demonstrates how hydrological thresholds create actionable bottlenecks: high river discharge suppresses crossings, while declining water levels rapidly restore connectivity and can trigger sudden surges in movement. From a forecasting perspective, monitoring discharge levels and seasonal precipitation trends can therefore provide early indications of impending slowdowns or renewed flows.

The practical value of climate coupling is not fully captured by aggregate validation metrics. Although incorporating weather data yields only modest improvements in overall arrival error, it substantially enhances anticipatory insight. By explicitly representing route closures, reduced travel speeds, and seasonal delays, the model identifies periods when populations are likely to experience interrupted journeys or extended transit times. This information is directly relevant for humanitarian logistics, including pre-positioning of supplies, camp capacity planning, transport coordination, and timing of field deployments. In this context, climate coupling improves operational preparedness even when statistical performance gains are moderate.

This added decision relevance comes at a computational cost. Integrating time-varying precipitation and discharge increases runtime by approximately $6.4\times$, primarily due to repeated data access, interpolation, and threshold evaluation across the network. While suitable for retrospective analysis and scenario exploration, this overhead constrains large ensemble simulations or near-real-time deployment. Targeted optimisation strategies, such as in-memory data storage, spatial indexing, caching, and parallel processing, could reduce computational burden and enhance feasibility for operational forecasting settings.

The framework is transferable to other regions, provided that climate thresholds are locally calibrated. Parameters derived for South Sudan reflect its rainfall regimes, terrain characteristics, and infrastructure conditions and may not generalise to areas with paved road networks, mountainous topography, or distinct hydrological behaviour. Applying the same evidence-based calibration process to region-specific climate records would maintain methodological consistency while ensuring contextual reliability for humanitarian use.

Several limitations should be acknowledged. First, the absence of detailed ground-truth data on route choice and movement behaviour under different weather conditions limits the extent to which the model can be directly validated at the corridor level. Second, the use of simplified thresholds and static route representations may not fully capture the complexity of terrain, infrastructure quality, and local travel behaviour. Third, while the South Sudan case provides a realistic and relevant setting, the derived thresholds and mobility patterns are context-specific and may not directly generalise to other regions with different environmental conditions, road networks, or infrastructure. Applying

this approach elsewhere would therefore require careful recalibration using local data. Addressing these limitations in future work would improve the robustness and transferability of the model.

6 Conclusion

This study introduced a systematic framework for integrating climatic variability into agent-based simulations of forced displacement. By coupling long-term precipitation and river-discharge data with a multiscale migration model, we demonstrated how environmental conditions shape mobility through dynamic changes in route accessibility and travel speeds. Applied to the 2016–2017 conflict in South Sudan, the climate-coupled simulations reveal that rainfall and flooding do not primarily determine whether populations flee, but instead regulate when, where, and how far they can travel. These effects manifest as seasonal slowdowns, route-level bottlenecks, and constrained movement during periods of high hydrological stress. Although climate coupling increases computational cost, it substantially improves the process realism and interpretability of displacement dynamics. By explicitly representing weather-driven accessibility constraints, the model provides insights that are directly relevant for humanitarian planning, including the identification of delayed movements and potential vulnerability windows along critical routes.

The main contributions of this work are threefold: (i) a reproducible Simulation Development Approach for embedding environmental data into displacement models, (ii) evidence-based threshold rules derived from four decades of reanalysis data, and (iii) an empirical demonstration of how climate factors alter displacement pathways and timings in practice. Together, these advances establish a transferable foundation for climate-aware modelling of forced migration. Future research should focus on strengthening empirical validation, refining context-sensitive mobility rules, and extending the framework toward operational forecasting. More broadly, integrating environmental processes into behavioural migration models represents an essential step toward realistic, data-driven tools for anticipating and managing displacement in a changing climate. These insights are particularly relevant for humanitarian organisations, as they highlight when and where mobility constraints are likely to occur and support more effective planning of interventions.

Acknowledgments. This work was supported by the HiDALGO and ITFLOWS projects that have received funding from the European Union Horizon 2020 research and innovation programme under grant agreements No 824115 and 882986. This paper expresses the opinions of the authors and not necessarily of the European Commission. The European Commission is not liable for any use that may be made of the information contained in this paper. It has also been supported by the Software Environment for Actionable and VVUQ-evaluated Exascale Applications (SEAVEA) project under the EPSRC grant (EP/W007711/1). We thank our colleagues from Poznan Supercomputing and Networking Center (PSNC), Marcin Lawenda and Piotr Dzierżak, for their support.

Code Availability The simulations in this study were performed using Flee version 2, available at <https://github.com/djgroen/flee/tree/v2.0>. All scripts that presented in this study are available from the authors upon request.

Disclosure of Interests. The authors have no competing interests to declare that are relevant to the content of this article.

References

1. D. Groen, “Development of a multiscale simulation approach for forced migration,” in *International Conference on Computational Science*, pp. 869–875, Springer, 2018.
2. S. Edwards, “Computational Tools in Predicting and Assessing Forced Migration,” *Journal of Refugee Studies*, vol. 21, pp. 347–359, sep 2008.
3. D. Groen, “Simulating refugee movements: Where would you go?,” *Procedia Computer Science*, vol. 80, pp. 2251–2255, 2016. International Conference on Computational Science 2016, ICCS 2016, 6-8 June 2016, San Diego, California, USA.
4. WorldBank, “A triumph over long odds: Building rural roads in South Sudan,” 2016.
5. UNICEF, “Rain, roads and checkpoints: The challenges of supplying South Sudan,” Jan 2018.
6. USAID, “South Sudan climate vulnerability profile: Sector and location-specific climate risks and resilience recommendations,” Aug 2019.
7. A. Jahani, H. Arabnejad, D. Suleimanova, M. Vuckovic, I. Mahmood, and D. Groen, “Towards a coupled migration and weather simulation: South Sudan conflict,” in *International Conference on Computational Science*, pp. 502–515, Springer, 2021.
8. C. Searle and J. van Vuuren, “Modelling forced migration: A framework for conflict-induced forced migration modelling according to an agent-based approach,” *Computers, Environment and Urban Systems*, vol. 85, p. 101568, 2021.
9. J. Anderson, A. Chaturvedi, and M. Cibulskis, “Simulation tools for developing policies for complex systems: Modeling the health and safety of refugee communities,” *Health care management science*, vol. 10, no. 4, pp. 331–339, 2007.
10. C. Lemos, H. Coelho, R. J. Lopes, *et al.*, “Agent-based modeling of social conflict, civil violence and revolution: State-of-the-art-review and further prospects,” in *EUMAS*, pp. 124–138, Toulouse, 2013.
11. Z. Mehrab, L. Stundal, S. Venkatramanan, S. Swarup, B. Lewis, H. S. Mortveit, C. L. Barrett, A. Pandey, C. R. Wells, and A. P. Galvani, “An agent-based framework to study forced migration: A case study of Ukraine,” *PNAS Nexus*, vol. 3, no. 3, p. pgae080, 2024.
12. M. Ghorbani, D. Suleimenova, A. Jahani, A. Saha, Y. Xue, K. Mintram, A. Anagnostou, A. Tas, W. Low, S. J. Taylor, and D. Groen, “Flee 3: Flexible agent-based simulation for forced migration,” *Journal of Computational Science*, vol. 81, p. 102371, 2024.
13. Y. Xue, T. Schincariol, T. Chadefaux, and D. Groen, “Using machine learning to forecast conflict events for use in forced migration models,” *Scientific Reports*, vol. 15, no. 1, p. 28202, 2025.

14. F. Boesjes, A. Jahani, B. Ooink, and D. Groen, "Analysing the effect of a dynamic physical environment network on the travel dynamics of forcibly displaced persons in Mali," *International Journal of Network Dynamics and Intelligence*, vol. 3, no. 1, p. 100003, 2024.
15. R. Black, W. N. Adger, N. W. Arnell, S. Dercon, A. Geddes, and D. Thomas, "The effect of environmental change on human migration," *Global environmental change*, vol. 21, pp. S3–S11, 2011.
16. M. N. Ahmed, G. Barlacchi, S. Braghin, F. Calabrese, M. Ferretti, V. P. A. Lonij, R. Nair, R. Novack, J. Paraszczak, and A. S. Toor, "A Multi-Scale Approach to Data-Driven Mass Migration Analysis.," in *SoGood@ ECML-PKDD*, p. 17, 2016.
17. L. Thalheimer, M. P. Schwarz, and F. Pretis, "Large weather and conflict effects on internal displacement in Somalia with little evidence of feedback onto conflict," *Global Environmental Change*, vol. 82, p. 102641, 2023.
18. A. I. Almulhim, G. N. Alverio, A. Sharifi, R. Shaw, S. Huq, M. J. Mahmud, S. Ahmad, and I. R. Abubakar, "Climate-induced migration in the global south: an in-depth analysis," *npj Climate Action*, vol. 3, p. 47, 2024.
19. E. I. B. Tsomb Tsomb, M. H. I. Nsoga Nsoga, and C. D. Bitting, "Climate change vulnerability and conflicts in Africa: evidence from the migrations channel," *Environmental Science and Pollution Research*, vol. 31, pp. 18811–18854, 2024.
20. K. Burrows and P. L. Kinney, "Exploring the climate change, migration and conflict nexus," *International journal of environmental research and public health*, vol. 13, no. 4, p. 443, 2016.
21. G. J. Abel, M. Brottrager, J. C. Cuaresma, and R. Muttarak, "Climate, conflict and forced migration," *Global Environmental Change*, vol. 54, pp. 239–249, 2019.
22. E. Ebooreime, O. Anjorin, C. Obi-Jeff, T. M. Ojo, and A. Hertelendy, "From drought to displacement: Assessing the impacts of climate change on conflict and forced migration in West Africa's Sahel region," *Journal of Climate and Society*, p. 100448, 2025.
23. H. H. Askland, B. Shannon, R. Chiong, N. Lockart, A. Maguire, and J. Rich, "Beyond migration: a critical review of climate change induced displacement," *Migration and Development*, vol. 11, no. 3, pp. 267–278, 2022.
24. T. Watson, T. Lenton, and R. Safra de Campos, "The climate change, conflict and migration nexus: A holistic view," *Climate and Development*, 2023.
25. Y. Xue, M. Li, H. Arabnejad, D. Suleimenova, A. Jahani, B. Geiger, F. Boesjes, A. Anagnostou, S. J. Taylor, X. Liu, and D. Groen, "Many-objective simulation optimization for camp location problems in humanitarian logistics," *International Journal of Network Dynamics and Intelligence*, vol. 13, no. 3, p. 100017, 2024.
26. D. Suleimenova, D. Bell, and D. Groen, "A generalized simulation development approach for predicting refugee destinations," *Scientific reports*, vol. 7, no. 1, pp. 1–13, 2017.
27. C. Raleigh, A. Linke, H. Hegre, and J. Karlsen, "Introducing acled: an armed conflict location and event dataset: special data feature," *Journal of peace research*, vol. 47, no. 5, pp. 651–660, 2010.
28. H. Hersbach, B. Bell, P. Berrisford, G. Biavati, A. Horányi, J. Muñoz Sabater, J. Nicolas, C. Peubey, R. Radu, I. Rozum, D. Schepers, A. Simmons, C. Soci, D. Dee, and J.-N. Thépaut, "Era5 hourly data on single levels from 1979 to present." 10.24381/cds.adbb2d471, 2018. [Accessed Feb. 11, 2021].
29. L. Alfieri, P. Burek, E. Dutra, B. Krzeminski, D. Muraro, J. Thielen, and F. Pappenberger, "Glofas–global ensemble streamflow forecasting and flood early warning," *Hydrology and Earth System Sciences*, vol. 17, no. 3, pp. 1161–1175, 2013.