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Extreme Weather Events and Internal Migration: Evidence from Mongolia

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Abstract
This article examines the effects of extreme weather events on internal migration in Mongolia. Our focus is on *dzuds*, extremely harsh winters characterized by very cold temperature, snowfall anomalies, and/or storms causing very high livestock mortality. We exploit exogenous variation in the intensity of extreme winter events across time and space to identify their causal impacts on permanent domestic migration. Our database is a time series of migration and population data at provincial and district level from official population registries, spanning the 1992-2018 period. Results obtained with a two-way fixed effects panel estimator show that extreme winter events cause significant and sizeable permanent out-migration from affected provinces for up to two years after an event. These effects are confirmed when considering net change rates in the overall population at the district level. The occurrence of extreme winter events is also a strong predictor for declines in the local population of pastoralist households, the socio-economic group most affected by those events. This suggests that the abandonment of pastoralist livelihoods is an important channel through which climate affects within-country migration.

Keywords Climate change · Extreme weather events · Internal migration · Mongolia

JEL R23 · Q54 · O13

MSC 62P20

Introduction

Extreme weather events, like droughts, floods, storms, and hot spells, cause considerable economic losses. Rural farm households in developing countries suffer more than others from such weather shocks due to their geographical exposure and their dependency on

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rain-fed agriculture (Harrington et al. 2018). In the absence of effective post-shock coping and long-term adaptation strategies, exposed households may resort to migration when climate-sensitive livelihoods are threatened by extreme weather events (Jha et al. 2018). The sudden occurrence of extreme weather events may lead to migration choices that are forced, rather than the result of a carefully planned process (Berlemann and Steinhardt 2017). If changing climatic conditions indeed matter for population mobility, the number of climate migrants is likely to accelerate in the years to come (Hunter and Nawrotzki 2016), as extreme weather events are predicted to increase both in their frequency and their intensity with global warming (Pachauri et al. 2014; WMO 2020). This outlook has stimulated an increased interest among policy stakeholders and the academic community alike in what role changing climatic conditions play as drivers for internal and international migration (Hoffmann et al. 2020).

The empirical literature on the climate-migration nexus has evolved rapidly in the new millennium (Berlemann and Steinhardt 2017). While most studies identify extreme weather conditions as a relevant driver for population mobility, the empirical evidence does not provide a clear-cut picture. Different results are obtained for internal and international migration as well as for the effects of gradual climate change and sudden weather events. The effect size also varies substantially across approaches and data used (Hoffmann et al. 2020). A further source of heterogeneity in results stems from the specific weather conditions and the institutional context considered. Besides climate, migration is also shaped by cultural, geographical, institutional, and socio-economic factors at the place of origin (Grecequet et al. 2017). In order to advance the state of knowledge, studies examining the climate-migration nexus in individual countries are particularly warranted (Berlemann and Tran 2020), as climate-related internal migration flows are more pronounced than cross-border migration (Hoffmann et al. 2020). This is particularly relevant in the context of developing countries, where internal migration is often more feasible and affordable to households as compared to costly international movements (Beine and Parsons 2015).

In this paper, we investigate internal migration dynamics in Mongolia. This East Asian country is particularly exposed to extreme winter events, locally referred to as *dzuds*, which puts Mongolia among the most severely affected countries by natural hazards globally (CRED 2020).[1] Such extreme winter events cause mass livestock mortality by starving or freezing animals to death. Through livestock mortality, winter events destroy the income, consumption, and asset base of pastoralist households, thereby directly threatening the livelihood of large parts of the rural population that live from animal husbandry. Our analysis aims at quantifying if, and to what extent, extreme winter events drive internal migration in Mongolia. We draw on a long time series of annual in- and out-migration and population data from population registries at the provincial and district level, spanning the 1992-2018 period. Using a two-way fixed effects panel estimator, we exploit spatial and temporal variation in the intensity of extreme winter events to identify the causal effects of these events on migration and population dynamics.

The exceptionally rich data at hand allow us to expand the existing literature on internal migration and climate in four ways. First, existing macro-level studies almost exclusively proxy internal migration with urbanization rates, a rather imprecise measure that overlooks certain forms of internal migration, such as rural-to-rural migration (Hoffmann

[1] In a 2020 report on the human costs of disasters over the 2000–2019 period, published by the Centre for Research on the Epidemiology of Disasters, Mongolia is ranked as the fifth most affected country when impacts are standardized to population size (CRED 2020, p. 20).

et al. 2020). In contrast, the availability of annual population registry data at the provincial and district levels allow us to study internal migration dynamics across administrative units throughout the country. Second, in existing micro-level studies that draw on population census data, a timely attribution of extreme weather events is complicated by long census intervals and potential biases stemming from self-reported migration information. Studying longer-term within-country migration dynamics using existing household panel surveys is also challenging, as panel surveys are scarce for developing countries and often only cover narrow regional settings and time periods. Against this backdrop, the yearly migration data at hand spanning almost three decades allow us to directly link the occurrence of extreme weather events with migration responses. Third, our analysis provides insights into the channels through which extreme weather events affect migration by considering net changes in the local population of pastoralist households whose livelihood is immediately affected by these events. Fourth, while existing studies on climate-induced migration focus on extreme temperatures (Hirvonen 2016; Thiede and Gray 2017), precipitation (Thiede et al. 2016), flood (Ruiz 2017), storms (Groeger and Zylberberg 2016; Koubi et al. 2016; Mahajan and Yang 2017), and drought (Dallmann and Millock 2017; Ruiz 2017), we provide evidence from another type of extreme weather event that has received less scholarly attention – extremely harsh winter conditions featuring extremely cold temperature, snowfall anomalies, and/or storms.

Results from the two-way fixed effects panel estimator show that extreme weather events occurring during the 1992-2018 period trigger significant and sizeable net out-migration from affected provinces for up to two years after an event. The finding is robust to the inclusion of time-varying controls for provincial characteristics. The district-level analysis confirms these results: We find a significant, negative, and strong effect of extreme weather events on the net population change rate across districts. Lastly, both province and district-level analyses reveal that extreme weather events significantly reduce the local population of pastoralist households.

The paper is organized as follows. Section 2 reviews the existing literature on climate-related internal migration dynamics. Sections 3 and 4 provide background information on extreme weather events and migration patterns in Mongolia. Section 5 introduces the empirical model and the data employed in the study. Results are discussed in section 6, while section 7 summarizes the key findings and concludes.

Review of the Evidence on Climate-Induced Internal Migration

The Intergovernmental Panel on Climate Change (IPCC) stressed the significance of climate-related migration and displacement as early as 1990. In that year, the IPCC put forth that the single most significant impact of climate change could be human migration, through the displacement of millions of people through the occurrence of shoreline erosion, coastal flooding, and agricultural disruption (Brown 2008). Since then, various predictive studies aimed at estimating the expected number of climate-induced migrants in the decades to come. For internal migration, Rigaud et al. (2018) estimate that without global and national climate action, climate change will displace more than 143 million people within their countries by the year 2050 in Sub-Saharan Africa, South Asia, and Latin America alone.

The empirical literature quantifying whether and how climate change affects migration flows only started to evolve in the early 2000s (Berlemann and Steinhardt 2017). With the increased availability of weather and migration data, the literature has developed rapidly since then. Existing studies differ in a number of dimensions, including the type of migration considered (international versus internal), the push factors analyzed (extreme weather events versus gradually changing climate), and the approach taken (micro versus macro). In the following, we outline developments and limitations in the empirical literature on climate and within-country migration.[2] The two main approaches used in existing research – macro-level approaches capturing gross migration flows and micro-level approaches building on survey and census data – are discussed in turn.

In the existing macro-level literature, internal migration flows are most commonly proxied by national urbanization rates (Hoffmann et al. 2020). For instance, Barrios et al. (2006) estimate the impact of rainfall shortages on urbanization patterns in a cross-country dataset, using a year- and country fixed effects approach. Findings suggest that declines in rainfall are an important determinant of urbanization in Sub-Saharan Africa. Applying a similar approach to fine-grained data, Henderson et al. (2017) exploit district-level heterogeneity in precipitation to analyze the determinants of urbanization rates across Sub-Saharan African countries and find that drier conditions increase urbanization in regions where cities are likely to be manufacturing centers. In contrast, in market cities that provide local services to farmers and lack structural transformation, drying has little impact on urbanization or total urban incomes. A positive link between rainfall shortages and urbanization is also documented by other studies of Sub-Sahara Africa (e.g., Brueckner 2012; Marchiori et al. 2012). Beine and Parsons (2015) examine urbanization in the aftermath of both sudden-onset disasters recorded by the Centre for Research on the Epidemiology of Disasters (CRED) as well as gradual changes in precipitation and temperature patterns, using cross-country data. When looking at the sub-sample of developing countries, Beine and Parsons find that extreme weather events significantly increase urbanization, while no significant effects are found for international migration. One limitation of these macro-level approaches is the rather narrow focus on rural-to-urban migration, thus providing an incomplete picture of overall internal migration dynamics (Hoffmann et al. 2020). Furthermore, the multi-country approach and, in turn, the usage of a country fixed effects specification makes it impossible to examine the role of socio-economic and contextual factors that are specific to individual countries.

Micro-level studies building on census or survey data from a single country are partly able to overcome these limitations as micro data usually allow controlling for a wide array of local characteristics (e.g., Carvajal and Pereira 2009; Goldbach 2017; Gray and Mueller 2012; Groeger and Zylberberg 2016; Koubi et al. 2016; Paul 2005). Given that surveys are often only collected in selected regions within a country, movements of whole households outside the survey area lead to attrition bias if households are not traced. For this reason, studies building on household survey data tend to focus on the determinants of migration decisions of individual household members. In most of these studies, variants of the gravity model are used as a flexible approach to modeling spatial interactions, assuming that migration varies with the degree of the force of attraction and is inversely proportional to distance (Poot et al. 2016). In more advanced applications, the gravity model is extended by variables representing economic, climatic, and other characteristics of the place of origin and destination (Tsegai and Bao Le 2010). Within this group of studies, gradual climate change and extreme weather events are often found to matter for migration (e.g.,

[2] A comprehensive overview of the literature is provided by Berlemann and Steinhardt (2017), Hoffmann et al. (2020), and Millock (2015).

Carvajal and Pereira 2009; Gray 2009; Groeger and Zylberberg 2016; Koubi et al. 2016). Notwithstanding, the overall evidence remains mixed, with other studies finding no systematic evidence of weather-induced within-country mobility (Bohra-Mishra et al. 2014; Di Falco et al. 2012; Goldbach 2017; Gray and Mueller 2012; Paul 2005).

Most closely related to our approach, another group of studies analyzes migration flows between regions by aggregating micro-level data to higher administrative divisions. In a study on Costa Rica, Robalino et al. (2015) analyze the impact of extreme weather events on internal migration flows over the 1995-2000 period. The authors use population census data from 2000, aggregated to the canton level, which are combined with the *DesInventar* database that records both the frequency and intensity of natural disasters, such as floods and landslides. In a gravity model framework, cross-canton gross migration rates are modeled as a function of population size, distance, as well as a set of push and pull factors that influence migration decisions, such as education levels, health infrastructure, security, and amenities. Robalino et al. find that natural disasters resulting in fatalities decrease out-migration, while the opposite holds for those disasters not causing numerous deaths. Using a similar approach, Saldana-Zorilla and Sandberg (2009) draw on population census data from Mexico, aggregated to the municipality level, and merge this database with secondary data on the occurrence of natural disasters. An increase in disaster frequency significantly increases out-migration from affected municipalities between 1990 and 2000. This effect is particularly pronounced in those regions defined as marginalized by government agencies, where agricultural production continues to constitute the main resource of livelihoods. In a study on Vietnam, Berlemann and Tran (2020) test if exposure to natural disasters cause households to temporarily or permanently emigrate from their communes. The database used in this study is commune-level data collected as part of a household panel survey implemented in 2012, 2014, and 2016. The measure of shock intensity – whether a given commune was affected by floods, typhoons, and droughts in the one and two years preceding each survey wave and whether each disaster type became worse over the last decade – is recorded from administrative officials in the commune questionnaire. Using a commune and year fixed effects approach, Berlemann and Tran show that droughts primarily cause temporary out-migration, while flood events tend to induce permanent out-migration from affected communes. In contrast, typhoons remain without any significant effects in both the short and the long runs.

Yet, studies building on micro-level data are often constrained by the quality and availability of suitable data. Specifically, there is a trade-off between the frequency of observations and geographical coverage in micro data, a common issue in the migration literature (Berlemann and Steinhardt 2017). While drawing on population census data allows for undertaking nationwide studies of internal migration, these are typically only available at five-year intervals. This makes a timely attribution of adverse weather effects difficult, which is problematic for sudden-onset disasters. Although socio-economic household surveys tend to be collected at shorter intervals, these are often limited in their geographical scope. In addition, household panel survey data is typically not available for long time horizons. This is especially the case for developing countries, where migration in response to adverse climatic conditions is likely to be most pronounced. Further, information on migration is usually self-reported through retrospective survey questions on censuses and surveys, while several studies also rely on measures of weather shocks that are self-reported by respondents. This renders studies based on micro-level data prone to reporting and reinterpretation biases.

We contribute to the existing literature by exploiting a long time series of annual in- and out-migration data at the provincial and district levels in Mongolia, which allows us to capture heterogeneity in the frequency and intensity of extreme weather events across time and space. The availability of yearly data allows us to attribute the effects of extreme weather events to migration patterns in the same year. From a methodological perspective, the rare possibility to exploit long-term population registry data at the sub-national level offers two advantages. First, as the measure of migration is based on reliable registration data, our analysis is not subject to reporting bias. Second, we capture migration rates across administrative units, while existing studies often have to draw on urbanization rates as an imprecise proxy for internal migration dynamics. Thus, our analysis overcomes common shortcomings of both micro- and macro-level studies on internal migration in the aftermath of extreme weather shocks.

Rural Livelihoods and Extreme Weather Events in Mongolia

Mongolia is already severely impacted by climate change. Temperature data recorded at weather stations across the country show that the annual mean air temperature has increased by 2.24 degrees Celsius between 1970 and 2015, a figure well above the global average (Ministry of Environment and Tourism 2018). Evidence also suggests that precipitation patterns and intensities are changing (Nandintsetseg et al. 2021; Goulden et al. 2016). Aside from gradual climatic changes, the country is increasingly exposed to extreme winter events (Palat Rao et al. 2015; Nandintsetseg and Shinoda 2015). In Mongolian, extreme winter events are referred to as *dzuds*, which literally means the mass deaths of livestock without attributing an exact underlying cause.[3] Extreme winter events may result from the interplay of several unfavorable weather phenomena, while the exact triggering conditions differ across winters (Lehmann-Uschner and Kraehnert 2018). The Mongolian language uses various terms to distinguish between different types of *dzud* (Hahn 2017, p. 42 f.; Murphy 2011, p. 32 f.): In *tsagaan dzud,* deep snow inhibits animals from reaching the grass underneath the snow cover, thus causing animal to die from starvation. A *khar dzud* is characterized by a lack of snow (often in combination with harsh and cold winter storms), thereby reducing the available forage and the main source of drinking water for animals during winter. A *tumer dzud* features excessive precipitation during the winter months, followed by a sudden temperature drop that creates a shield of ice that is impenetrable for animals and, in turn, leads to animal starvation. A *khuiten dzud* is characterized by extremely low temperatures, causing animals freezing to death, which may occur jointly with harsh winter storms. Lastly, a *khavsarcan dzud* is identified by a combination of deep snow and extremely cold temperature.

Extreme winter events have severe impacts on the rural economy, especially the agricultural sector. In 2018, 40% of the labor force living outside of the capital of Ulaanbaatar derived their livelihood solely from animal husbandry (NSO 2021). Herding continues to be the single most important occupation in rural areas. Most pastoralist households keep large shares of their wealth in their herds, holding an average of 288 animals as of 2018 (ibid.). The five most commonly held species – goats, sheep, horses, cattle, and camels – not only provide food and income to households but also serve as collateral for loans (Hahn 2017). Practicing an extensive system of livestock production, Mongolian

[3] Murphy (2011, p. 42 f.) highlights that, unlike earthquakes or hurricanes, which can also strike and be measured in uninhabited regions, the term *dzud* is only used to refer to events in which livestock die as a result of extreme conditions of some kind.

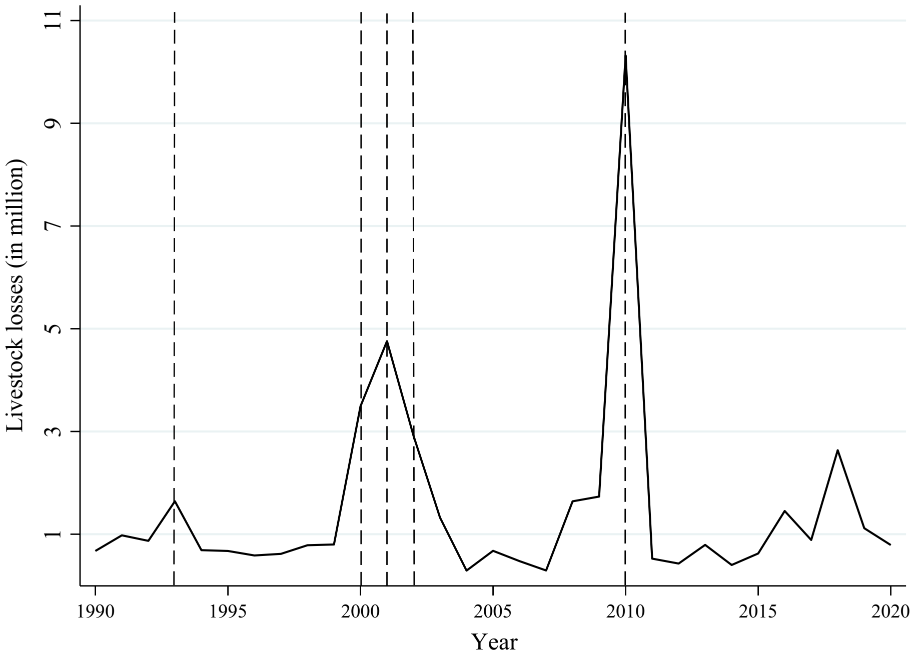

Fig. 1 Annual livestock losses in Mongolia, 1990-2020. Note: The vertical dashed lines indicate years when extreme winter events affected large parts of the country (while in some further years, extreme winter events occurred in specific regions). Livestock losses are the sum of losses across the five dominant species (goats, sheep, horses, cattle, and camels). Source: Mongolia Livestock Census

pastoralists graze their animals on open rangelands year-round, which makes them directly dependent on weather conditions. Most, though not all, pastoralists are either semi or fully nomadic, moving their herd between two and 14 times per year (Teickner et al. 2020), typically performing the same cycle of movements every year. Extreme winter events that cause livestock to freeze to death or die of starvation within short periods of time pose an immediate threat to the viability of pastoralist livelihoods (Hahn 2017). Sudden mass livestock mortality is often aggravated if drought conditions in the preceding summer led to a situation where animals are not starting the winter months at full strength (Palat Rao et al. 2015).

Extreme winter events have occurred throughout Mongolian history. However, such events have become both more frequent and more severe, with historic records indicating that 15 extreme winter events in the eighteenth century were followed by 31 extreme winter events in the nineteenth century and 43 events in the twentieth century (Hahn 2017). Figure 1 illustrates that five extreme winter events that affected large parts of the country occurred between 1992 and 2018, the period under study here. Further extreme events occurred in specific regions over this time period.

With more than 10 million dead animals, the 2009/10 extreme winter caused roughly 24% of the total national livestock to die, the largest livestock losses recorded in a single winter in the last 50 years (NSO 2021). Some 40% of all herding households lost more than half of their herd during the 2009/10 winter (UNDP NEMA 2010). With these tremendous losses of livestock, it can take years for herders to rebuild their herds

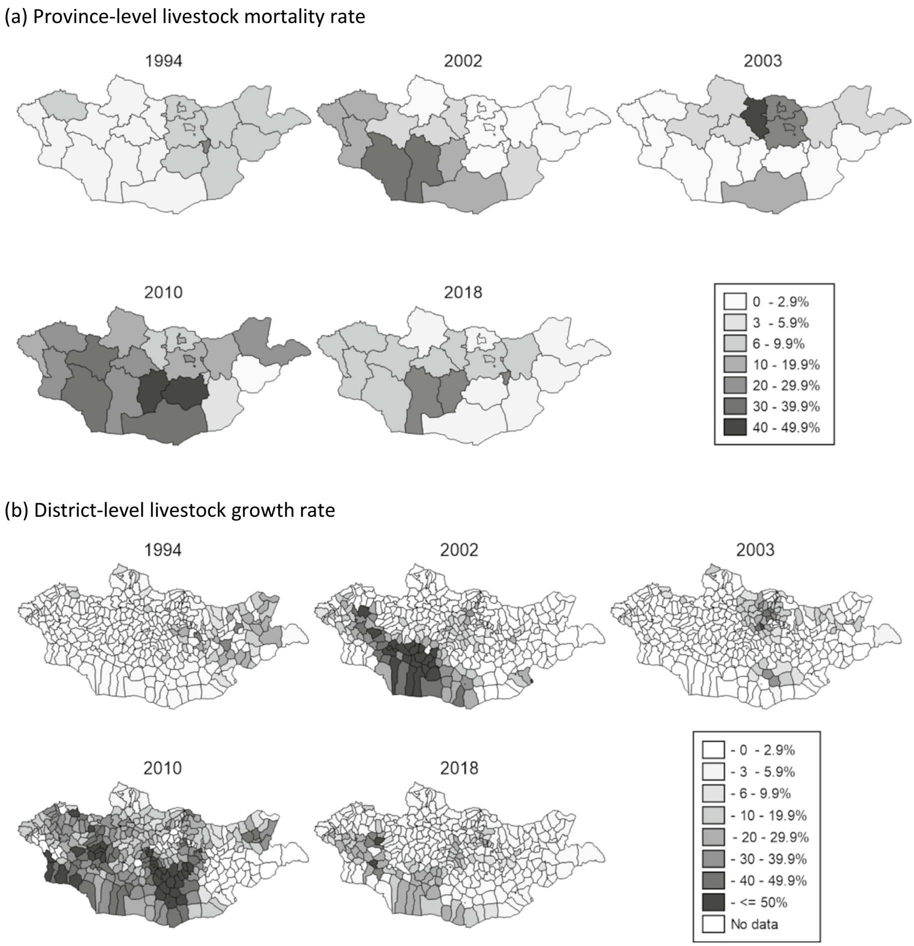

Fig. 2 Spatial variation in livestock mortality in selected years. **a** Province-level livestock mortality rate. **b** District-level livestock growth rate. Note: Livestock mortality and growth rates are calculated as the average across the five dominant species (goats, sheep, horses, cattle, and camels). Source: Mongolia Livestock Census

following an extreme winter event (Bertram-Huemmer and Kraehnert 2018). Exposure to extreme winter events also increases the likelihood that pastoralists are forced to abandon the herding economy (Lehmann-Uschner and Kraehnert 2018), particularly if their herd size is pushed below the threshold of 100 animals that is often considered the minimum necessary for sustaining a pastoralist livelihood in the long term (Goodland et al. 2009). There is also large spatial heterogeneity in the intensity of any given extreme winter event (Middleton et al. 2015). Figure 2 shows that different areas of the country were hit by extreme events in different years, while their intensity differed even across neighboring provinces and districts.

Migration Patterns in Mongolia

Throughout the twentieth century and beyond, internal migration has played an important role in Mongolia (IOM 2018a). In the era of centrally planned economy, influenced by the Soviet Union, industrial centers were established in urban areas across the country. While migration was controlled by the administration, large parts of the rural population were attracted to these centers because of employment prospects (Guinness and Guinness 2012). Thereby, the share of the urban population rose dramatically. The fall of the Iron Curtain brought profound political changes and the collapse of wide parts of the industrial sector. The resulting freedom of movement led to reverse migration dynamics from urban to rural areas (ibid.). The herding economy offered a promising prospective for many Mongolian families, as livestock ownership was privatized and collectives disappeared.

Since the late 1990s, Mongolia has experienced renewed rural to urban migration, in particular to the capital of Ulaanbaatar. The percentage of Mongolians living in urban areas increased from 53% in 1995 to 68% in 2018 (NSO 2021). From one million inhabitants in 2007, Ulaanbaatar grew to 1.5 million in 2018 (United Nations 2021). Most migrants arriving in Ulaanbaatar seek shelter in the so-called *ger* districts, where most dwellings are traditional Mongolian tents (*gers*) (Sigh et al. 2017). In 2014, approximately 60% of Ulaanbaatar's population lived in these districts, which are mostly located on the outskirts of the city (Engel 2015). As many of the *ger* districts formed in a hastily and uncontrolled way, they are often poorly connected to urban utilities and infrastructure. Many inhabitants have to buy and fetch drinking water from government-run kiosks, overall sanitation is poor, and waste removal is organized irregularly (Henreckson 2018). As dwellings in *ger* districts are poorly insulated and stoves are fired by coal or other biomass, *ger* districts are hotspots for air pollution, especially in winter.

Intensive urbanization is a major topic in Mongolian politics and urban planning. At the beginning of 2017, the governor of Ulaanbaatar, together with the mayor of the capital, issued a law officially prohibiting domestic permanent migration from rural areas to the capital city (IOM 2018b). In 2018, the migration ban was extended to the beginning of 2020 (NSO 2020). As the law prevents migrants from rural areas from registering in the capital, the number of unregistered migrants in Ulaanbaatar has risen. Without an official resident status, it is difficult to find stable employment and impossible to access basic services, such as schools, daycare, health care, and social welfare, causing high vulnerability among unregistered migrants (IOM 2018b).

In the Mongolian context, the driving forces of internal migration are not well understood. The few existing qualitative studies associate rural to urban migration dynamics with poverty, low agricultural incomes at origin, income opportunities at destination, environmental degradation, and climate change (IOM 2018a; IOM 2018b; Guinness and Guinness 2012). We are only aware of a single study, by Xu et al. (2021), that examines the drivers of internal migration with a quantitative approach, using cross-sectional data from the Mongolian Labor Force Surveys implemented in 2006, 2010, and 2014. Xu et al. find that being male, young, better educated, and married are strong predictors for rural to urban migration decisions of single household members. Yet, the analysis does not examine the effects of extreme winter events on migration.

Empirical Strategy

We exploit plausibly exogenous variation across time and space in the occurrence of extreme winter events to study their impacts on internal migration dynamics. We estimate the following two-way fixed effects model:

$$M_{i,t} = \beta_1 extreme\ event_{i,t,(t-1;t-3)} + \beta_2 C_{i,t} + \alpha_i + \lambda_t + \mu_i t + \varepsilon_{i,t} \quad (1)$$

As the outcome of interest, we employ various proxies for internal migration $M_{i,\ t}$, measured at province (or district) i in year t. *Extreme event*$_{i,\ t}$ measures the intensity of an extreme winter event in a given province (or district) and year. Several lags of this measure are included to examine the timing of migration in the aftermath of such events. $C_{i,\ t}$ is a vector of time-varying control variables. Province (or district) fixed effects α_i control for the unobserved time-constant heterogeneity across administrative units. Year fixed effects λ_t capture events and developments affecting all administrative units in the same way, while province- (or district-) specific linear time trends $\mu_i t$ control for different long-run trends in migration figures of individual provinces (or districts). $\varepsilon_{i,\ t}$ denotes the unexplained residual. Standard errors are clustered at the province (or district) level.

The empirical analysis builds on data at the level of provinces and districts, the first- and second-level administrative subdivision of Mongolia, respectively. Aside from the capital city, the country consists of 21 provinces (*aimags*), which are subdivided into 331 districts (*soums)*. The capital of Ulaanbaatar is subdivided into nine so-called *düüregs*, which are often considered equivalent to districts. In the empirical analysis, we follow this categorization and, furthermore, treat Ulaanbaatar as one province. Our sample consists of 22 provinces and 340 districts, for which yearly data spanning the 1992-2018 period is available.

Province-Level Analysis

The first outcome is the net migration rate per province and year, which we calculate as follows:

$$M(net\ migration\ rate)_{i,t} = \frac{\left(I_{i,t} - E_{i,t}\right)}{\left(P_{i,t}/1{,}000\right)} \quad (2)$$

where $I_{i,\ t}$ stands for the number of in-migrants entering province i during year t, $E_{i,\ t}$ captures the number of out-migrants leaving province i during year t, and $P_{i,\ t}$ is the mid-year population of province i in year t. A positive value reflects net immigration, a situation where an excess of persons are entering a given province, while a negative value mirrors net emigration, a situation where an excess of persons are leaving a given province. Specifically, a value of −10 in the net migration rate for a given year means that 10 out of 1000 inhabitants leave their province in the course of one year. Across all provinces and years, the net migration rate has a negative mean (−10.3) because of international out-migration.[4] Data on the number of in- and out-migrants and the total population come from official population records maintained by the National Statistical Office of Mongolia (NSO 2013). Mongolian law requires migrants to de-register at their place of origin and re-register at

[4] Note that the mean does not account for population sizes in respective provinces. The mean national-level net migration rate is −0.169 for the 1992-2018 period.

destination within ten days after moving. Note that this outcome does not capture temporary migration, for instance, individuals searching for seasonal employment outside of their registered place of residence or nomadic herders crossing province boundaries as part of their annual cycle of movements. One limitation that goes along with using official registration data is that it does not capture any form of unofficial movements of migrants who either choose not to register or are banned from registering at their destination.[5] Our results should be considered as lower bound estimates of total internal migration.

The second outcome is the net change rate in the local number of pastoralist households,[6] the socio-economic group we expect to be most immediately affected by extreme weather events:

$$M(net\ change\ rate\ pastoralist\ households)_{i,t} = \frac{\left(PPbegin_{i,t} - PPend_{i,t}\right)}{\left(PPmid_{i,t}/1{,}000\right)} \tag{3}$$

where $PPbegin_{i,\ t}$ is the number of pastoralist households in province i at the beginning of year t, $PPend_{i,\ t}$ is the number of pastoralist households in province i at the end of year t, and $PPmid_{i,\ t}$ represents the mid-year number of pastoralist households in province i and year t.

We proxy the intensity of extreme winter events with livestock mortality per province and year. Livestock mortality is considered an appropriate measure for the intensity of such events (Murphy 2011; Skees and Enkh-Amgalan 2002).[7] The data come from the annual Mongolia Livestock Census, which the NSO has been implementing since 1918. Each year in December, enumerators record the number of livestock held by herders across the country as well as the number of livestock that died in the previous 12 months, both broken down for each of the five commonly held species. Based on this historical data, we proxy the occurrence of an extreme winter event with a dummy variable taking the value of one if the average livestock mortality rate across species exceeds 6% for a given province and year. Our choice of the 6% threshold is informed by the operating index-based livestock insurance, where a livestock mortality rate of 6% triggers indemnity payouts to insured households.[8] We employ an alternative threshold as well as the continuous livestock mortality rate as robustness test.

[5] A survey conducted by the International Organization for Migration in 2018 of some 1000 migrant households arriving in the provinces of Selenge, Dornogovi, and Ulaanbaatar, finds that only one-third of the migrant households registered within the legal timeframe (IOM 2018a). In urban areas of Selenge and Dornogovi, about 93 and 71% of the surveyed households registered, respectively, while in Ulaanbaatar only 49% registered. While the high number of non-registered migrants in the capital is likely due to the migration ban, the figures suggest that a considerable share of migrants remains unregistered.

[6] The NSO defines pastoralist households as one or several herders and their nuclear family who conduct livestock husbandry around the year for their main purpose of livelihood and source of income (NSO 2015). The number of pastoralist households is recorded each year in December as part of the Mongolia Livestock Census.

[7] Modeling the intensity of extreme winter events with weather data is challenging because the specific weather conditions triggering each extreme winter vary considerably across events. As outlined in section 3, triggering conditions include, but are not limited to, extremely cold temperature, harsh winter storms, excessive snowfall, rainfall combined with sudden temperature drops, as well as summer-season drought conditions. Among climate scientists modeling extreme weather events in Mongolia, there is no consensus regarding what weather data and variables best measure the intensity of extreme winter events (Tachiiri et al. 2008; Palat Rao et al. 2015; Nandintsetseg et al. 2018).

[8] Note, however, that a livestock mortality rate of 6% at the *district* level triggers index insurance payouts, while we define livestock mortality at the *province* level.

To select a set of province-level control variables, we draw on the existing literature that employs variants of the gravity model for migration (e.g., Berlemann and Tran 2020; Borjas 1987; Dallmann and Millock 2017; Tsegai and Bao Le 2010).[9] To proxy the local economic performance, we include the revenue of the provincial government, which consists of tax income; revenues from interests, dividends, and fines; as well as transfers and grants from the central government and the fund for local development. Another economic measure is the unemployment rate, which reflects the economic attractiveness of a province. As proxy for the quality of the local infrastructure, we account for the number of households with access to portable water. As this indicator does not represent the situation of all nomadic households, we additionally include the total number of water supply stations per province.[10] The number of physicians per 10,000 inhabitants is used as measure for the quality of health care provision. Lastly, we employ the share of students continuing from the first to the fifth grade as proxy for the quality of the local educational system. Overcontrolling is an issue that often arises when quantifying the impact of major shocks on an outcome variable in a gravity model framework (Berlemann and Steinhardt 2017; Dell et al. 2014). If a control variable is in itself influenced by the shock, any empirical migration model that includes such control is likely to capture only partial effects of the shock on the outcome (Berlemann and Tran 2020). We approach this issue by presenting results both obtained from a model without controls and with the full set of controls.

District-Level Analysis

We further estimate migration dynamics at the district level, which increases the number of observations by factor 15. As data on the number of migrants is not publicly available at the district level, we employ the net population change rate as a proxy for overall migration dynamics as main outcome, which we define as follows:

$$M(net\ population\ change\ rate)_{i,t} = \frac{\left(Pbegin_{i,t} - Pend_{i,t}\right)}{\left(Pmid_{i,t}/1{,}000\right)} \tag{4}$$

with $Pbegin_{i,\,t}$ representing the resident population in district i at the beginning of year t, $Pend_{i,\,t}$ stands for the population in district i at the end of year t, and $Pmid_{i,\,t}$ is the mid-year population of district i in year t. Besides migration, the net population change rate is also shaped by the number of births and deaths.[11] A value of −10 in the net population change rate for a given year means that the district population decreased by 10 out of 1000 inhabitants in the course of one year. The second outcome is the net change rate in the total number of pastoralist households per district, which is calculated analogously to eq. 3 above.

[9] The gravity model assumes that individuals compare characteristics between destination and origin region and maximize their utility while accounting for the cost of migration. Aside from wage differentials, regional attributes, such as infrastructure, environmental conditions, and socio-economic characteristics at origin and destination are typically taken into account (Tsegai and Bao Le 2010). For Mongolia, only single-sided migration data is available at an aggregate level, which renders it impossible to estimate a full gravity model. Instead, we refer to the gravity model in more general terms as a reference point for selecting control variables.

[10] Water supply stations are wells designated to supply drinking water. Wells are either connected to the central water supply system or filled by water tank trucks of authorized entities.

[11] We did not come across reports of human casualties caused by extreme winter conditions.

For the period of interest, annual district-level data from the Mongolia Livestock Census is only available for the total number of living animals (by species), but not for the number of deceased animals. We approximate the district-level livestock mortality with year-to-year changes in overall livestock numbers.[12] To proxy the occurrence of an extreme winter event, we define a dummy variable that takes the value of one if the yearly growth rate in total livestock numbers across species is below −6% for a given district and year. As no time-varying controls are available at the district level, we employ the same controls as in the province-level analysis.

Summary statistics of the key variables of interest are tabulated in Table 1.

Results

Results from the baseline two-way fixed effects OLS regression on the determinants of the province-level net migration rate are displayed in Table 2. When considering the impact of extreme winter events on the net migration rate in the same year (column 1), the estimated coefficient of the extreme events proxy is negative, indicating higher total emigration, albeit not statistically significant at conventional levels. When lagging the shock measure by one year (column 2), the effect size more than triples in magnitude and is statistically significant at the 1% level. The occurrence of an extreme winter event on average decreases the net migration rate by 7.045 in the year after the event strikes. This corresponds to a net out-migration of more than 7 individuals per 1000 or 0.7% of the provincial population. This is a sizable effect, constituting roughly 70% of the sample mean and 36% of the standard deviation.[13] The effect of extreme winter events on the net migration rate in affected provinces remains statistically significant (at the 10% level), although it is slightly smaller in magnitude, two years after an extreme weather event (column 3). Exposure to such events has no significant effect on net migration rates three years after an event (column 4). Column 5 displays results when including the full set of time-varying province-level controls in model 2, which yields the strongest results.[14] The effect of the extreme event is highly significant, though smaller in magnitude compared to the model without controls. This is in line with expectations, as more and possibly endogenous controls absorb parts of the total effect. In column 6, we interact the shock proxy with the five regions of Mongolia. The marginal effects of the lagged extreme weather event on the net migration rate for individual regions are negative and significant in the Western, Khangai, and Central regions, while it is positive and significant for the capital city of Ulaanbaatar. This finding is in line with qualitative reports suggesting that internal migration in Mongolia is particularly driven by rural-to-urban migration.

All baseline results hold when we restrict the sample to a more narrow time window, including the 1995-2018 period, the 1992-2016 period, and the 1995-2016 period (Table 7 in the Appendix). These findings assure us that potential anomalies in the net migration

[12] District-level data on the number of deceased animals is only available from 2012 onwards. For the 2012-2018 period, the coefficient of correlation between the annual livestock mortality rate and annual livestock growth rate is 0.51. We conclude that both measures are reasonably comparable.

[13] Qualitatively similar findings are obtained (but not displayed here) when using the net migration in absolute terms, net out-migration, or net out-migration rate as outcome.

[14] Similar results are obtained (but not displayed here) when including the set of time-varying controls in models 1 and 3.

Table 1 Summary statistics

		Mean	St. Dev.	Min	Max	Obs.
(A) PROVINCE-LEVEL ANALYSIS						
Dependent variables						
Net migration rate		−10.3	19.6	−236.7	65.5	594
Net change rate in number of pastoralist households		−10.4	55.8	−338.4	229.9	594
Net change rate in number of pastoralist households	owning 1-50 animals	−55.8	127.7	−327.1	761.9	352
Net change rate in number of pastoralist households	owning 51-100 animals	−39.6	148.4	−1450.9	1576.6	352
Net change rate in number of pastoralist households	owning 101-200 animals	−2.47	92.1	−496.7	320.2	352
Net change rate in number of pastoralist households	owning 201-500 animals	58.4	156.5	−723.9	536.6	352
Net change rate in number of pastoralist households	owning 501-999 animals	142.3	293.8	−1135.1	1259.3	352
Net change rate in number of pastoralist households	owning more than 1000 animals	169.3	365.6	−1333.3	1200	352
Controls						
Extreme weather event (livestock mortality rate > 6%)		0.17	0.37	0	1	594
Extreme weather event (livestock mortality rate > 15%)		0.06	0.23	0	1	594
Livestock mortality rate (in %)		0.04	0.06	0.0006	0.45	594
Revenue of local government (in million Mongolian Tugrik)		19,196	69,529	139	846,659	484
Unemployment rate		6.73	4.51	0.30	29.2	484
Number of households with access to portable water		13,758	25,825	438	202,044	484
Number of water supply stations		50.3	100.1	1	827	484
Number of physicians per 10,000 inhabitants		20.4	7.71	11.1	54.1	484
Percent of students continuing to 5th grade		81.2	15.8	0	106.4	484
(B) DISTRICT-LEVEL ANALYSIS						
Dependent variables						
Net population change rate		−0.38	63.5	−1423	1401	9064
Net change rate in female population		−1.40	66.2	−1435	1400	9064
Net change rate in male population		0.63	66.5	−1412	1403	9064

Table 1 (continued)

	Mean	St. Dev.	Min	Max	Obs.
Net change rate in number of pastoralist households	−6.40	105.5	−1764	1687	9062
Controls					
Extreme weather event (livestock growth rate < −6%)	0.18	0.38	0	1	8855
Livestock growth rate (in %)	0.05	0.16	−0.72	1.55	8855

All variables are displayed as within-unit averages over time, using data from 1992 to 2018. Source: Mongolian Statistical Information Service and Mongolia Livestock Census

Table 2 Determinants of net migration rate at the province level, 1992-2018

	(1)	(2)	(3)	(4)	(5)	(6)
Extreme weather event	−1.996					
	(0.615)					
Extreme weather event lag1		−7.045***			−6.399***	
		(0.001)			(0.007)	
Extreme weather event lag2			−5.229*			
			(0.064)			
Extreme weather event lag3				2.297		
				(0.302)		
Government revenue (log)					3.677*	
					(0.058)	
Unemployment rate					−0.0298	
					(0.894)	
Number households with water access (log)					1.451	
					(0.508)	
Number of water supply stations (log)					−0.212	
					(0.873)	
Number of physicians per 10,000 inhabitants					−0.135	
					(0.747)	
Percent of students continuing to 5th grade					0.0338	
					(0.808)	
Extreme weather event lag1 # Western region						−9.231***
						(0.002)
Extreme weather event lag1 # Khangai region						−9.180***
						(0.010)
Extreme weather event lag1 # Central region						−7.096***
						(0.010)
Extreme weather event lag1 # Ulaanbaatar						4.386*
						(0.086)
Extreme weather event lag1 # Eastern region						−3.382
						(0.136)
Constant	−746.7***	−794.1***	−763.1***	−672.5***	964.3*	−798.2***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.055)	(0.000)
R-squared	0.257	0.268	0.263	0.256	0.320	0.272
Province FE	yes	yes	yes	yes	yes	yes
Year FE	yes	yes	yes	yes	yes	yes
Province-level time trend	yes	yes	yes	yes	yes	yes
Number of provinces	22	22	22	22	22	22
Number of years	27	27	27	27	22	27
Observations	594	594	593	592	484	594

Estimated with OLS with standard errors clustered at the province level. P-values in parentheses with * $p<0.10$, ** $p<0.05$, *** $p<0.01$. The dependent variable, the net migration rate per province, is calculated as absolute net migration over the mid-year population times 1000. Source: Mongolian Statistical Information Service and Mongolia Livestock Census

rate in the direct aftermath of the fall of the Iron Curtain and the migration ban to Ulaanbaatar enacted in 2017 are not individually or jointly driving the results. In a further robustness test, we only consider the most extreme events, in which the annual livestock mortality rate exceeded 15% in a given province and year (Table 8 in the Appendix). As in the baseline specification, the effect of particularly severe extreme events on the net migration rate is statistically significant and economically large one year after the event (column 2). In contrast to baseline results, the effect is also significant in the year the disaster occurs (column 1). We obtain similar findings – statistically significant and sizable effects of livestock mortality on the net migration rate in the same year as well as one and two years later – when proxying shock intensity with a continuous measure of livestock mortality (Table 9 in the Appendix).[15]

Table 3 displays results from the district-level model. The outcome is now defined more broadly as the net population change rate, which, besides migration, is also shaped by the number of births and deaths. Results confirm the patterns found in the baseline model: The occurrence of a local extreme weather event significantly and strongly lowers the population in districts up to two years after an extreme event (column 1-3), while the effect is no longer significant three years after an event (column 4). Again, the estimated effect remains comparable in terms of significance level and magnitude when including the full set of time-varying controls (column 5). The inclusion of regional interaction terms in column 6 shows that the negative effects on the population change rate are particularly pronounced in the Western and Khangai regions. When differentiating between the net population change rate among the female population (column 7) and the male population (column 8), the estimated coefficients of extreme weather events are of similar size (we cannot reject the null hypotheses of equality of coefficients, with the p value of a Wald chi square test accounting for the simultaneous (co)variance matrix of the coefficients of extreme weather events being 0.47). This suggests that entire households migrate as response to extreme events.

Next, we investigate the effects of extreme winter events on the net change rate of pastoralist households, the population sub-group whose livelihood is most immediately affected by such events and climate change in general (Table 4). The occurrence of an extreme event significantly reduces the number of pastoralist households in affected districts in the year the disaster strikes by about 6% (column 1). The effect becomes smaller, but remains significant at the 1% level, one year after the disaster (column 2). Including the full set of time-varying controls yields similar results (column 5).[16] When differentiating the effect by region (column 6), we find that extreme events significantly reduce the population of pastoralists in all five regions of Mongolia, including Ulaanbaatar.

Lastly, we explore how extreme winter events affects the number of pastoralist households with different herd sizes. We separately estimate the model for seven wealth categories of pastoralist households: (1) households with less than 51 heads of livestock, (2) 51-100 livestock, (3) 101-200 livestock, (4) 201-500 livestock, (5) 501-999 livestock, and (6) 1000 and more livestock. Data on the number of pastoralist households in each wealth category in each province is collected as part of the annual Mongolia Livestock Census.

[15] Qualitatively similar results are obtained when employing alternative outcome variables, such as total out-migration in absolute terms or the net out-migration rate.

[16] The estimated coefficient of the shock variable is larger in magnitude in column 5 compared to the model without controls (column 1). Note that several controls have missing values, which reduces the sample size considerably. When estimating column 1 on the same reduced sample as in column 5, the estimated coefficients are very similar in magnitude.

Table 3 Determinants of net population change rate at the district level, 1992-2018

	Whole population						Female population	Male population
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Extreme weather event	−11.82***							
	(0.000)							
Extreme weather event lag1		−14.01***			−10.89***		−14.70***	−13.21***
		(0.000)			(0.000)		(0.000)	(0.000)
Extreme weather event lag2			−10.01***					
			(0.000)					
Extreme weather event lag3				−0.677				
				(0.730)				
Government revenue (log)					15.30***			
					(0.000)			
Unemployment rate					−0.634**			
					(0.026)			
Number households with water access (log)					−1.210			
					(0.757)			
Number of water supplystations (log)					1.142			
					(0.790)			
Number of physiciansper 10,000 inhabitants					−0.0801			
					(0.601)			
Percent of students continuingto 5th grade					−0.0772			
					(0.928)			
Extreme weather event lag1 # Western region						−26.63***		
						(0.000)		
Extreme weather event lag1# Khangai region						−17.04***		
						(0.001)		

Table 3 (continued)

	Whole population						Female population	Male population
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Extreme weather event lag1# Central region						−3.937		
						(0.262)		
Extreme weather event lag1# Ulaanbaatar						−4.984		
						(0.500)		
Extreme weather event lag1# Eastern region						−3.204		
						(0.540)		
Constant	−711.1***	−647.2***	−631.8***	−614.1***	1764.1	−526.2***	−1040.6***	−202.3
	(0.000)	(0.000)	(0.000)	(0.000)	(0.176)	(0.001)	(0.000)	(0.191)
R-squared	0.146	0.149	0.146	0.149	0.153	0.152	0.139	0.138
Province FE	yes	yes	yes	yes	yes	yes	yes	yes
Year FE	yes	yes	yes	yes	yes	yes	yes	yes
District-level time trend	yes	yes	yes	yes	yes	yes	yes	yes
Number of districts	339	339	339	339	339	339	339	339
Number of years	27	27	27	27	22	27	27	27
Observations	8826	8816	8803	8790	7172	8816	8816	8816

Estimated with OLS with standard errors clustered at the district level. P-values in parentheses with * $p<0.10$, ** $p<0.05$, *** $p<0.01$. The dependent variable, the net population change rate per district, is calculated as absolute net population change over the mid-year population times 1000. Source: Mongolian Statistical Information Service and Mongolia Livestock Census

Table 4 Determinants of net change rate in the number of pastoralist households at the district level, 1992-2018

	(1)	(2)	(3)	(4)	(5)	(6)
Extreme weather event	−59.64***				−66.77***	
	(0.000)				(0.000)	
Extreme weather event lag1		−20.92***				
		(0.000)				
Extreme weather event lag2			1.974			
			(0.502)			
Extreme weather event lag3				7.202		
				(0.136)		
Government revenue (log)					1.606	
					(0.760)	
Unemployment rate					0.132	
					(0.712)	
Number households with water access (log)					−10.66**	
					(0.041)	
Number of water supply stations (log)					11.74**	
					(0.020)	
Number of physicians per 10,000 inhabitants					−2.488**	
					(0.011)	
Percent of students continuing to 5th grade					−0.186	
					(0.403)	
Extreme weather event # Western region						−58.87***
						(0.000)
Extreme weather event # Khangai region						−52.91***
						(0.000)
Extreme weather event # Central region						−64.05***
						(0.000)
Extreme weather event # Ulaan-baatar						−54.77***
						(0.000)
Extreme weather event # Eastern region						−64.08***
						(0.001)
Constant	7487.2***	8456.9***	8815.2***	8695.5***	14,036.9***	7404.2***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
R-squared	0.131	0.0924	0.0862	0.0874	0.132	0.132
District FE	yes	yes	yes	yes	yes	yes
Year FE	yes	yes	yes	yes	yes	yes
District-level time trend	yes	yes	yes	yes	yes	yes
Number of districts	339	339	338	338	339	339
Number of years	27	27	27	27	22	27
Observations	8832	8811	8790	8769	7190	8832

Estimated with OLS with standard errors clustered at the district level. P-values in parentheses with * $p<0.10$, ** $p<0.05$, *** $p<0.01$. The dependent variable, the net change rate in the number of pastoralist households per district, is calculated as absolute net change of the population of pastoralist households over the mid-year population of pastoralist households times 1000. Source: Mongolian Statistical Information Service and Mongolia Livestock Census

Table 5 Determinants of net change rate in the number of pastoralist households by wealth at the province level, 2003-2018

	All pastoralist households	Pastoralist households with:					
		1-50 animals	51-100 animals	101-200 animals	201-500 animals	501-999 animals	over 1000 animals
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Extreme weather event	-45.330^{***}	77.347^{***}	15.055	-78.347^{***}	-196.337^{***}	-465.713^{***}	-534.668^{***}
	(0.000)	(0.008)	(0.362)	(0.010)	(0.000)	(0.000)	(0.000)
Constant	-3921.4^{***}	$-15,606.9^{***}$	-7479.7^{***}	2278.3	$21,544.4^{***}$	$28,009.0^{***}$	$41,616.8^{***}$
	(0.001)	(0.000)	(0.004)	(0.395)	(0.000)	(0.002)	(0.001)
R-squared	0.358	0.526	0.133	0.238	0.526	0.552	0.575
Province FE	yes	yes	yes	yes	yes	yes	Yes
Year FE	yes	yes	yes	yes	yes	yes	Yes
Province-level time trend	yes	yes	yes	yes	yes	yes	Yes
Number of provinces	22	22	22	22	22	22	22
Number of years	16	16	16	16	16	16	16
Observations	352	352	352	352	352	352	352

Estimated with OLS with standard errors clustered at the province level. P-values in parentheses with * $p<0.10$, ** $p<0.05$, *** $p<0.01$. The dependent variable, the net change rate in the number of pastoralist households per province, is calculated as absolute net change of the population of pastoralist households over the mid-year population of pastoralist households times 1000. Source: Mongolian Statistical Information Service and Mongolia Livestock Census

Table 6 Autocorrelation in province-level livestock mortality rate, 1992-2018

	Province fixed effects				Arellano-Bond
	(1)	(2)	(3)	(4)	(5)
Livestock mortality rate lag1	−0.0351	−0.0403	−0.0448	−0.0466	−0.0702
	(0.411)	(0.344)	(0.296)	(0.276)	(0.042)
Livestock mortality rate lag2		−0.0859**	−0.0867**	−0.0944**	
		(0.044)	(0.043)	(0.027)	
Livestock mortality rate lag3			−0.0602	−0.0691	
			(0.159)	(0.106)	
Livestock mortality rate lag4				−0.0505	
				(0.236)	
R-squared	0.509	0.513	0.515	0.519	
Province FE	yes	yes	yes	yes	yes
Year FE	yes	yes	yes	yes	yes
Number of provinces	22	22	22	22	22
Number of years	27	27	27	27	26
Observations	594	593	592	591	570

Models in columns 1-4 estimated with OLS, using 1 to 4 year lags of the dependent variable as explanatory variables. Column 5 displays results of an Arellano-Bond estimation with 4 lags of the dependent variable used as instruments. Robust standard errors in parentheses with * $p<0.10$, ** $p<0.05$, *** $p<0.01$. The dependent variable is livestock mortality rate per province. Source: Mongolia Livestock Census

Province-level data is available for 2003 through 2018.[17] Table 5 displays results. When using the net change rate in the total number of pastoralist households per province as outcome, irrespective of wealth (column 1), we obtain qualitatively similar findings as in the district-level analysis for the 1992-2018 time period displayed in Table 4. When differentiating the effects by wealth category (columns 2-7), we find that extreme winter events significantly reduce the number of pastoralist households owning more than 100 heads of livestock. Indeed, the effect size is largest (−53%) for the wealthiest category of pastoralists owning more than 999 heads of livestock and becomes smaller with decreasing herd size. In contrast, extreme winter events have a significant and positive impact (8%) on the net change rate of pastoralist households in the poorest wealth category who own 1-50 heads of livestock (column 2). We draw two conclusions from these results. First, the occurrence of extreme winter events not only reduces the total number of Mongolian pastoralist households over time. It also increases the number of pastoralists with marginal herd sizes that are considered too small to sustain a herding livelihood in the long term in the harsh Mongolian environment. The poorest category of herders is particularly vulnerable to the impacts of future extreme events. Hence, there is reason to expect that the downward trend in the population of pastoralists will persist if extreme weather events continue to strike in the future. Second, it appears that livestock wealth does not protect households from the adverse effects of extreme winter events, as even the group of wealthiest pastoralists diminishes after such events. This again underlines the sheer magnitude of such extreme events.

[17] We are very grateful to Banzragch Nandintsetseg for sharing this data.

Robustness

One potential threat for our identification strategy is potential positive autocorrelation across extreme weather events over time, which would result in biased estimates. If the occurrence of extreme weather events is positively autocorrelated, inhabitants of strongly exposed areas may systematically differ in their migration behavior from households in low-risk areas. In order to test for positive autocorrelation across events, the province-level livestock mortality rate for the 1992-2018 time period is regressed on its lagged values in a two-way fixed effects model (Table 6). In addition, we employ an Arellano-Bond estimator. Across specifications, we only find significant effects of livestock mortality lagged by two years on livestock mortality in the current year. As none of the employed models reports positive effects, positive autocorrelation and foresighted migration decisions should not be a major concern.

As an additional falsification test, the baseline model is estimated with lead values of the shock proxy (Table 10 in the Appendix). In line with our expectations, extreme weather events that lie 1, 2, or 3 years in the future do not have significant effects on the province-level net migration rate (columns 1-3, respectively).

Conclusion

Our analysis documents that the occurrence of extreme weather events is an important push factor for internal migration in Mongolia. The country is increasingly affected by extremely harsh winters that result in very high livestock mortality, thereby threatening the livelihood of large parts of the rural population. We examine the causal impacts of extreme winter events on internal migration spanning the 1992-2018 period in a two-way fixed effects panel estimator, drawing on migration and population data at the province and district levels.

Findings show that extreme winter events have significant, negative, and sizeable effects on internal migration in Mongolia. The local occurrence of an extreme winter event triggers net outmigration from affected provinces and reduces the overall population in affected districts. Reductions in the local population are strongest in the year an event strikes and remain statistically significant up to two years following an event. The negative effects on population dynamics are particularly pronounced in the Western and Khangai regions. Results are robust to the inclusion of time-varying controls, alternative definitions of the shock proxy and the outcomes, as well as the censoring of the data to more narrow time windows. Furthermore, results do not appear to be driven by positive autocorrelation of extreme weather events over time.

Moreover, the local occurrence of extreme winter events significantly and strongly reduces the population of pastoralist households. This effect is observed across all regions of Mongolia, including the capital city. Wealthiest pastoralists, owning 1000 animals or more, face the strongest reductions in their population size in the aftermath of a winter event. In contrast, the group of pastoralists in the poorest wealth group, owning up to 50 animals, grows significantly in the aftermath of an extreme winter.

One limitation of our study is that with the official population registry data at hand, we are unable to capture informal migration where individuals either chose not to register or are banned from registering. Additionally, temporary migration, such as seasonal employment, is not covered by the available data. The obtained results should be interpreted as the lower bound of actual effects.

Extreme winter events in Mongolia have been increasing in both intensity and frequency throughout the 20th century and beyond (Hahn 2017). The pressure on the herding economy as well as migration responses to weather disasters will in all likelihood further intensify. This has three policy implications: First, there is a need to accommodate a growing urban population, especially in the capital city. This may warrant investments in urban infrastructure, for instance by expanding the water supply network, sewage system, electricity grid, transport system, as well as educational and medical services. Former pastoralists may need to acquire labor market qualifications tailored to the urban job market, while the demand for job opportunities in urban areas will likely rise in general. Second, there is the need to assist pastoralists in adapting to and better coping with future extreme events. Index-based livestock insurance (Bertram-Huemmer and Kraehnert 2018) and early action cash transfers (FAO 2018) appear to be promising tools. Third, more generically, there is a need to foster climate change mitigation and to avoid high-end climate scenarios.

Appendix

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Data Availability The datasets generated during and/or analyzed during the current study are publically available from the Mongolian Statistical Information Service repository, https://www.1212.mn

Code Availability The econometric analysis in this study was implemented using the STATA software. The code to replicate the findings are available from the corresponding author upon request.

Declarations

Conflicts of Interest/Competing Interests We, Julian Roeckert and Kati Kraehnert, declare that we have no conflict of interest.

Table 7 Robustness test: Determinants of net migration rate at the province level in different time windows

	1995-2018			1992 -2016			1995-2016		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Extreme weather event lag1	−5.775**		−5.554**	−7.248***		−6.399***	−5.598**		−5.554**
	(0.012)		(0.017)	(0.001)		(0.007)	(0.022)		(0.017)
Extreme weather event lag2		−2.387			−5.373*			−2.227	
		(0.152)			(0.083)			(0.226)	
Government revenue (log)			4.387*			3.677*			4.387*
			(0.055)			(0.058)			(0.055)
Unemployment rate			−0.142			−0.0298			−0.142
			(0.498)			(0.894)			(0.498)
Number households with water access (log)			0.360			1.451			0.360
			(0.879)			(0.508)			(0.879)
Number of water supply stations (log)			1.029			−0.212			1.029
			(0.475)			(0.873)			(0.475)
Physician density			0.180			−0.135			0.180
			(0.651)			(0.747)			(0.651)
Percent of students continuing to 5th grade			0.0598			0.0338			0.0598
			(0.689)			(0.808)			(0.689)
Constant	−1207.6***	−1192.2***	−233.4	−828.0***	−793.2***	964.3*	−1314.5***	−1297.8***	−233.4
	(0.000)	(0.000)	(0.650)	(0.000)	(0.000)	(0.055)	(0.000)	(0.000)	(0.650)
R-squared	0.417	0.405	0.366	0.248	0.242	0.320	0.361	0.348	0.366
Province FE	yes	yes	yes	yes	yes	yes	yes	yes	yes
Year FE	yes	yes	yes	yes	yes	yes	yes	yes	yes
Province-level time trend	yes	yes	yes	yes	yes	yes	yes	yes	yes
Number of provinces	22	22	22	22	22	22	22	22	22
Number of years	24	24	21	25	25	22	22	22	21

Table 7 (continued)

	1995-2018			1992 -2016			1995-2016		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Observations	528	528	462	550	549	484	484	484	462

Estimated with OLS with standard errors clustered at the province level. P-values in parentheses with * $p<0.10$, ** $p<0.05$, *** $p<0.01$. The dependent variable, the net migration rate per province, is calculated as absolute net migration over the mid-year population times 1000. Source: Mongolian Statistical Information Service and Mongolia Livestock Census

Table 8 Robustness test: Determinants of net migration rate at the province level with different threshold of the shock proxy, 1992-2018

	(1)	(2)	(3)	(4)	(5)	(6)
Livestock mortality rate > 15%	−9.442***					
	(0.002)					
Livestock mortality rate > 15%, lag1		−6.798**			−5.916**	
		(0.016)			(0.030)	
Livestock mortality rate > 15%, lag2			−3.591			
			(0.208)			
Livestock mortality rate > 15%, lag3				−5.233		
				(0.118)		
Government revenue (log)					3.900*	
					(0.055)	
Unemployment rate					0.0371	
					(0.879)	
Number water supply stations (log)					1.395	
					(0.556)	
Number of households with water access (log)					−0.566	
					(0.693)	
Percent of students continuing to 5th grade					−0.167	
					(0.688)	
Number of physicians per 10,000 inhabitants					0.0508	
					(0.698)	
Livestock mortality rate > 15%, lag1# Western region						−10.05***
						(0.000)
Livestock mortality rate > 15%, lag1# Khangai region						−9.063**
						(0.017)

Table 8 (continued)

	(1)	(2)	(3)	(4)	(5)	(6)
Livestock mortality rate > 15%, lag1# Central region						−2.732
						(0.547)
Livestock mortality rate > 15%, lag1# Ulaanbaatar						−0.882
						(0.710)
Livestock mortality rate > 15%, lag1# Eastern region						−2.081
						(0.442)
Constant	−659.7***	−678.1***	−688.3***	−676.8***	1166.2**	−703.9***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.034)	(0.000)
R-squared	0.266	0.261	0.258	0.257	0.309	0.263
Province FE	yes	yes	yes	yes	yes	yes
Year FE	yes	yes	yes	yes	yes	yes
Province-level time trend	yes	yes	yes	yes	yes	yes
Number of provinces	22	22	22	22	22	22
Number of years	27	27	27	27	22	27
Observations	594	594	593	592	484	594

Estimated with OLS with standard errors clustered at the province level. P-values in parentheses with * $p<0.10$, ** $p<0.05$, *** $p<0.01$. The dependent variable, the net migration rate per province, is calculated as absolute net migration over the mid-year population times 1000. Source: Mongolian Statistical Information Service and Mongolia Livestock Census

Table 9 Robustness test: Determinants of net migration rate at the province level with continuous shock proxy, 1992-2018

	(1)	(2)	(3)	(4)	(5)	(6)
Livestock mortality	−44.386***				−45.917***	
	(0.003)				(0.002)	
Livestock mortality lag1		−41.059***				
		(0.000)				
Livestock mortality lag2			−24.381**			
			(0.034)			
Livestock mortality lag3				−13.252		
				(0.106)		
Government revenue (log)					3.345*	
					(0.095)	
Unemployment rate					0.002	
					(0.992)	
Number households with water access (log)					1.288	
					(0.575)	
Number of water supply stations (log)					−0.379	
					(0.780)	
Physician density					−0.248	
					(0.519)	
Percent of students continuing to 5th grade					0.053	
					(0.690)	
Livestock mortality # Western region						−77.554***
						(0.000)
Livestock mortality # Khangai region						−38.458***
						(0.005)

Table 9 (continued)

	(1)	(2)	(3)	(4)	(5)	(6)
Livestock mortality # Central region						−24.232
						(0.306)
Livestock mortality # Ulaanbaatar						−39.073***
						(0.005)
Livestock mortality # Eastern region						−55.891***
						(0.009)
Constant	−762.7***	−745.2***	−746.6***	−720.4***	926.4**	−715.8***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.048)	(0.000)
R-squared	0.270	0.268	0.260	0.255	0.333	0.276
District FE	yes	yes	yes	yes	yes	yes
Year FE	yes	yes	yes	yes	yes	yes
District-level time trend	yes	yes	yes	yes	yes	yes
Number of provinces	22	22	22	22	22	22
Number of years	27	27	27	27	22	27
Observations	594	594	593	592	484	594

Estimated with OLS with standard errors clustered at the province level. P-values in parentheses with * $p<0.10$, ** $p<0.05$, *** $p<0.01$. The dependent variable, the net migration rate per province, is calculated as absolute net migration over the mid-year population times 1000. Source: Mongolian Statistical Information Service and Mongolia Livestock Census

Table 10 Robustness test: Determinants of net migration rate at the province level with lead values of the shock proxy, 1992-2018

	(1)	(2)	(3)	(4)
Extreme weather event lead1	3.672			0.292
	(0.352)			(0.902)
Extreme weather event lead2		2.477		
		(0.509)		
Extreme weather event lead3			4.920	
			(0.152)	
Government revenue (log)				3.603*
				(0.084)
Unemployment rate				0.0001
				(0.999)
Number households with water access (log)				1.472
				(0.540)
Number of water supply stations (log)				−0.573
				(0.704)
Physician density				−0.178
				(0.668)
Percent of students continuing to 5th grade				0.0611
				(0.654)
Constant	−636.7***	−658.8***	−594.3***	1100.7**
	(0.000)	(0.000)	(0.000)	(0.042)
R-squared	0.259	0.257	0.262	0.300
Province FE	yes	yes	yes	yes
Year FE	yes	yes	yes	yes
Province-level time trend	yes	yes	yes	yes
Number of provinces	22	22	22	22
Number of years	27	27	27	22
Observations	594	593	592	484

Estimated with OLS with standard errors clustered at the province level. P-values in parentheses with * $p<0.10$, ** $p<0.05$, *** $p<0.01$. The dependent variable, the net migration rate per province, is calculated as absolute net migration over the mid-year population times 1000. Source: Mongolian Statistical Information Service and Mongolia Livestock Census

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