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Nonlinear permanent migration response to climatic variations but minimal response to disasters

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We present a microlevel study to simultaneously investigate the effects of variations in temperature and precipitation along with sudden natural disasters to infer their relative influence on migration that is likely permanent. The study is made possible by the availability of household panel data from Indonesia with an exceptional tracking rate combined with frequent occurrence of natural disasters and significant climatic variations, thus providing a quasi-experiment to examine the influence of environment on migration. Using data on 7,185 households followed over 15 y, we analyze whole-household, province-to-province migration, which allows us to understand the effects of environmental factors on permanent moves that may differ from temporary migration. The results suggest that permanent migration is influenced by climatic variations, whereas episodic disasters tend to have much smaller or no impact on such migration. In particular, temperature has a nonlinear effect on migration such that above 25 °C, a rise in temperature is related to an increase in outmigration, potentially through its impact on economic conditions. We use these results to estimate the impact of projected temperature increases on future permanent migration. Though precipitation also has a similar nonlinear effect on migration, the effect is smaller than that of temperature, underscoring the importance of using an expanded set of climatic factors as predictors of migration. These findings on the minimal influence of natural disasters and precipitation on permanent moves supplement previous findings on the significant role of these variables in promoting temporary migration.

human response to climate change | environmental migrants | migration and disasters | climate change | statistical

Human migration has been identified as a potentially important response to climate change. Where climate change makes habitation in certain places less desirable or even impossible, people may respond by moving elsewhere. However, the idea that environmental change induces people to migrate remains a widely contested topic, especially given recent findings suggesting that environmental changes may also constrain movement (1–3). Historically, there has been a paucity of empirical demonstrations of environmental effects on population mobility, partly due to sparse data and partly because migration studies have tended to focus on further exploration of social and economic predictors of migration that have already been established as primary drivers. More recently however, new empirical approaches to exploring the relationship between migration and climate change have emerged.

Based on a review of the existing literature (*SI Text, Literature Review*), there is conflicting evidence on the effects of climatic variations and natural disasters on migration, partly arising from the inability to distinguish permanent moves from temporary ones, especially in the case of macrolevel studies that analyze aggregate flows of people. Furthermore, the effects may vary significantly by distance of migration destination, which may also confound the overall effect of environmental factors on migration. Above all, most studies at the microlevel do not simultaneously examine the effects of both disasters and climatic changes on migration, and often use only one aspect of climate, generally variation in rainfall. However, precipitation and temperature are historically correlated and to infer an unbiased effect of either one on migration probability, both need to be included in the model (4).

The current study therefore attempts to improve on the existing studies. This study is, to our knowledge, the first at a microlevel to simultaneously explore the effects of sudden natural disasters and climatic variations on permanent migration of the whole household. (Household migration can take several forms: migration of a single member or individual migration; migration of one or more members of the household or split household migration; and migration of whole household, which includes migration of the entire household along with the head of household.) In doing so, we test the effect of temperature along with precipitation on migration decision. We include a summary that allows a quick comparison of the methodology used in our study compared with previous studies in terms of the choice of environmental variables to predict migration (Table S1). Prior studies have primarily examined individual migration behavior, which may capture both temporary and permanent migration. In contrast, province-level migration of entire households, as we show (with the use of data that follows households over a period of 15 y), tends to be more permanent. (We hereafter use the term "permanent.") To our knowledge, the only other studies that focus on household migration explore the mechanisms by which natural disasters can deter migration of the household or its relatives (5, 6). By studying migration behavior of the whole household, we are able to focus on permanent migration, and therefore directly test how sudden disasters along with variations in rainfall and temperature affect permanent and

Significance

In the context of global climate change and increasing impact of some types of natural disasters, there has been significant interest in investigating the influence of climatic factors on human migration. We explore a more comprehensive set of climatic factors than used in most previous work to predict the effects of sudden natural disasters and climatic variations on migration. By following province-to-province movement of more than 7,000 households in Indonesia over a decade and a half, this study reveals that an increase in temperature (e.g., due to natural variations or global warming) and, to a lesser extent, variations in rainfall are likely to have a greater effect on permanent outmigration of households than natural disasters.

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relatively longer distance (province-to-province) migration as opposed to temporary movement; this allows us to complement the findings in some existing studies that generally conclude that natural disasters and rainfall result in temporary and short-distance moves while providing new evidence on the temperature–migration link in the context of microlevel studies.

To achieve these goals, we chose Indonesia as our study site because as the world's largest archipelago situated in a tectonically active location, the country is highly exposed to both geologic and climatic hazards (*SI Text, Background on Indonesia*). In addition, as the world's fourth most populous country with ~40% of the labor force engaged in agriculture and more than 60% of the total population living in the coastal areas, the country is extremely vulnerable to the impacts of climate variations and extreme events (*SI Text, Background on Indonesia*). At the same time, the availability of household panel data with an exceptional tracking rate allows us to use a difference-in-differences approach to study the migration of households before and after disasters as well as establish a plausibly causal link between climatic variations and migration. We use the Indonesian Family Life Survey (IFLS), a household panel survey representative of ~83% of the Indonesian population from 13 of the 27 provinces in 1993 (Fig. S1). The IFLS provides data on 7,185 original households, followed over a period of 15 y (*Materials and Methods*). The migration outcome we predict captures migration of households, which is likely permanent. We track whole-household migration for a 15-y period during which the original households are followed with a very high retention rate even after they migrate. Some 95% of the migrant households end up migrating only once and do not return to their original province during the entire 15-y period. Therefore, at least in the Indonesian case, the provincial level migration of households seems to be permanent (see *SI Text, Internal Migration in Indonesia*, for more on internal migration in Indonesia).

The household panel data are supplemented with data on natural disasters taken from DesInventar database, which provides disaster-related data using information on disasters of different intensities based on preexisting official data, academic records, newspaper sources, and institutional reports. Different types of disasters may not all affect migration in the same way, thus cancelling out each other's effects on migration. For our analysis, we therefore separately estimate the effects of each type of disaster. Furthermore, we use multiple measures to capture the different ways in which a disaster may affect the population, for three primary reasons. First, we believe that the intensity of disaster rather than simply the occurrence of disaster should more accurately predict its effect. Measures such as number of deaths, number injured, number of houses destroyed, and amount of financial loss (captured by monetary loss measured in Indonesian Rupiah) from each type of disaster aggregated at the province level are used to capture both the frequency as well as the intensity of disasters. Second, relying on a single measure of a disaster may not capture its overall effect because a certain event may result in large financial losses but inflict little physical harm. Third, using alternate measures of disaster allows one to compare and confirm results, and can be used as a robustness check (*Materials and Methods*).

Finally, for measures of climatic variations, we construct estimates of average temperature and precipitation for each province during each observation interval (*Materials and Methods*), because temperature and rainfall variations together provide a more complete measure of the extent of climate variations that may affect migration (7).

Results

To identify the impact of climatic variations and sudden disasters on household migration, we exploit our panel data structure, which allows us to use random variations in the incidence of disasters and weather patterns experienced by households over time. We run an empirical model, which predicts annual probability of migration due to the effects of random multi-year variations in temperature, precipitation, and disasters measured over the period that coincides with the period for which migration is observed as captured in the equation below:

$$M_h(t) = \alpha_1 T_p(t_1) + \alpha_2 T_p^2(t_1) + \alpha_3 R_p(t_1) + \alpha_4 R_p^2(t_1) + \sum_{i=1}^{4} \beta_i X_{ip}(t_1) + \sum_{n=1}^{10} \mu_n Z_{nh}(t_1 - t + 1) + P_p + T(t) + \varepsilon_h(t),$$

where, $M_h(t)$ is the probability per annum that household h migrates to another province within time period t, where t is defined as periods 1993–1997, 1997–2000, and 2000–2007 (*Materials and Methods*). We introduce a quadratic function of temperature (T) and precipitation (R) with coefficients α_1 and α_2 representing the quadratic effects of average temperature, whereas α_3 and α_4 capture the quadratic effects of average annual precipitation on annual outmigration probability. The weather variables are measured for period t_1 in province p where household h originally resides with t_1 representing the most recent years of exposure that includes small possible lag effects. We define t_1 as 1992–1997, 1996–2000, and 1999–2007 for the corresponding migration flows recorded for 1993–1997, 1997–2000, and 2000–2007, respectively. Similarly, β_1 to β_4 represent the effects of the disaster variables (X) such as the total number of deaths from the four types of disasters i that resulted during period t_1 in province p where household h resides originally.

The household's propensity to migrate may be affected by a number of household level characteristics (Z). For example, migrants are often self-selected by their level of financial and human capital as well as the demographic characteristics of the household head (8, 9). The coefficient μ_n therefore represents the effects of household-level characteristics such as value of a household's assets used as a proxy of household's wealth; whether the household owns a nonfarm business; whether the household is a farming household; ownership of house; and the household's size. Among the demographic attributes of the household head, we control for sex, age, and education. All these variables are measured at the beginning of each time period t captured by ($t_1 - t + 1$; e.g., 1993 household characteristics are used for 1993–1997 migration flow, and so on).

According to economic theory, people respond to geographic wage differentials and migrate where the expected returns exceed the expected costs of movement (10). More developed provinces with better opportunities and higher wages could therefore provide an economically more attractive environment for migrants. Thus, we control for province fixed effects represented by P_p, which also account for migration due to social capital or network effect at the provincial level (*SI Text, Social Capital Effect*) by controlling for province-level characteristics that are likely to be correlated with environmental variables and may also influence migration. To avoid correlating trends in our predictors of interest, other variables, and our migration outcome, we also account for common trend behaviors by including year fixed-effects represented by $T(t)$ in all of our models. These year fixed-effects account for any unobservable common climatic shocks, such as the El Niño Southern Oscillation (ENSO), which could be correlated with temperature exposure as well as migration outcomes. These fixed effects also account for other factors that are common across the sample that may affect migration trends, including factors such as policy changes, economic cycles, political events, and technological advancements.

We use the above specification but with different measures of disasters in the next three sets of regressions. In other words, the variable X, which represents the number of deaths due to each

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disaster in our baseline specification, is later replaced with number injured, houses destroyed, and financial losses from the four types of disasters. In all regressions, we report heteroskedasticity-robust SEs using multidimensional clusters that account for correlations within each province year and any within-household correlation over time (11). Households simultaneously present in a common province are exposed to the same local job market, level of development, culture of migration, etc. The migration pattern of a household might also be correlated across time. Consequently, there is a possible correlation within household and within province years, which we adjust for in our SE estimates.

Similarly, spatial autocorrelation, especially in weather patterns attributable to ENSO events, may cause neighboring provinces to share spatially correlated disturbances. Although our year effects will control for average effects that are common across the sample, it will not be able to account for any spatial heterogeneity in spatial correlation; to account for this, we collapse our household level data to the province-year level and predict the provincial outmigration rate of households over time using a SE estimator that accounts for both spatial autocorrelation across provinces as well as temporal autocorrelation within provinces (12). This approach dramatically reduces our sample size, making our results somewhat conservative, but it allows us to account for spatial and temporal autocorrelation as well as correlation within province years. The results we discuss below are robust using this conservative approach (Table S2).

Table 1 summarizes results on the effects of temperature, precipitation, and disasters on annual migration probability using four different measures of disasters (see Table S3 and *SI Text, Effects of Household Characteristics on Migration*, for results on the effects of household level characteristics). Using each measure of disaster, we summarize results with and without the household-level predictors of migration. For example, results in the first two columns use number of deaths as measure of disaster with the left-hand side column being the base model and the right-hand side column representing the full model with household level controls. All eight regressions consistently establish a significantly nonlinear effect of temperature on migration. The turning point value is at 25 °C, which means below the period-average temperature of 25 °C, any increase in temperature reduces outmigration, but above 25 °C a rise in temperature is related to an increase in outmigration. These results are comparable to previous findings where the turning point for average annual temperature was 23.5 °C (13, 14).

Fig. 1 presents the partial effect of temperature on migration, which clearly shows the nonlinear effect of temperature. We find that above 25 °C, outmigration increases nonlinearly with temperature such that a 1 °C increase in temperature from 26 °C to 27 °C increases the annual probability of migration by 0.008 (0.8% points), but an increase from 27 °C to 28 °C raises the annual outmigration probability by 0.014, holding other variables constant.

Next, in all of the regressions there is a consistent significantly nonlinear effect of precipitation on migration, which appropriately captures the expectations for the rainfall–migration link at the extremes (Fig. 1). The turning point value is at ~2.2 m of average annual precipitation, which suggests that below the period-average annual precipitation of 2.2 m, any increase in rainfall reduces outmigration, but above it, any increase in rainfall increases outmigration such that with a rise in precipitation from 2.3 m to 3.3 m for example, a household's annual migration probability goes up by 0.00146. The effect, however, is much smaller compared with the effect of temperature on migration, which is consistent with previous findings that even agriculture-related outmigration is mostly sensitive to temperature rather than precipitation (15).

With respect to the effects of disasters, these generally do not have a large, consistent, or significant effect on migration with the signs changing depending on the measure of disaster used except in the case of landslides. In all cases, the small or zero effects of disaster are precisely estimated, allowing us to rule out positive or negative effects that are large in magnitude. Unlike other types of disasters, landslides tend to have a consistent positive effect on migration, which are marginally significant in the models that use houses destroyed and deaths as measures of disasters. A 1% increase in deaths and houses destroyed from landslides raises annual migration probability of households by 0.000006 and 0.000004, respectively. The effects of other disaster variables tend not to be significant or consistent in sign across different models. We estimate a positive effect of earthquakes more often than not and a negative effect of floods in general, which appears significant in the model using houses destroyed as measures of the impact of flood: each percentage increase in

Table 1. Annual probability of household migration regressed on temperature, precipitation, and natural disasters using four alternate measures of disasters

	Disasters measured							
Independent variables	Deaths		Injured		Houses destroyed		Financial losses	
Temperature	−0.150058**	−0.143237**	−0.147825***	−0.144591***	−0.121127***	−0.116311***	−0.171172***	−0.165246***
	(0.060404)	(0.058426)	(0.056667)	(0.055843)	(0.045832)	(0.044488)	(0.060111)	(0.057540)
Temperature squared	0.002991**	0.002858**	0.002894***	0.002835**	0.002407***	0.002307***	0.003420***	0.003301***
	(0.001226)	(0.001187)	(0.001119)	(0.001104)	(0.000921)	(0.000894)	(0.001204)	(0.001153)
Precipitation	−0.025357**	−0.025215**	−0.023690***	−0.023455***	−0.022128***	−0.022207***	−0.018942**	−0.019557***
	(0.010877)	(0.010589)	(0.008853)	(0.008880)	(0.008237)	(0.008121)	(0.007482)	(0.007475)
Precipitation squared	0.005745**	0.005798**	0.005909**	0.005915**	0.005800***	0.005848***	0.004176**	0.004357**
	(0.002781)	(0.002735)	(0.002413)	(0.002440)	(0.002076)	(0.002057)	(0.001762)	(0.001777)
Earthquake	−0.000005	−0.000013	0.000012	0.000011	0.000160*	0.000153*	0.000031	0.000033
	(0.000134)	(0.000133)	(0.000109)	(0.000109)	(0.000092)	(0.000092)	(0.000060)	(0.000063)
Eruption	−0.000823*	−0.000830**	0.000886	0.000765	0.001314*	0.001224*	–	–
	(0.000425)	(0.000404)	(0.000663)	(0.000651)	(0.000714)	(0.000686)	–	–
Flood	−0.000158	−0.000103	−0.000211	−0.000160	−0.000604**	−0.000587**	0.000274	0.000279
	(0.000429)	(0.000421)	(0.000215)	(0.000206)	(0.000248)	(0.000240)	(0.000179)	(0.000170)
Landslide	0.000688*	0.000609*	0.000783	0.000724	0.000441**	0.000412*	0.000152	0.000130
	(0.000368)	(0.000345)	(0.000488)	(0.000465)	(0.000223)	(0.000216)	(0.000116)	(0.000116)
Observations	19,525	19,398	19,525	19,398	19,525	19,398	19,525	19,398

Logarithmic transformation of measures of disasters and household asset value used. All results control for province and time fixed effects. SEs (in parentheses) corrected using multidimensional clustering. ***$P < 0.01$, **$P < 0.05$, *$P < 0.1$.

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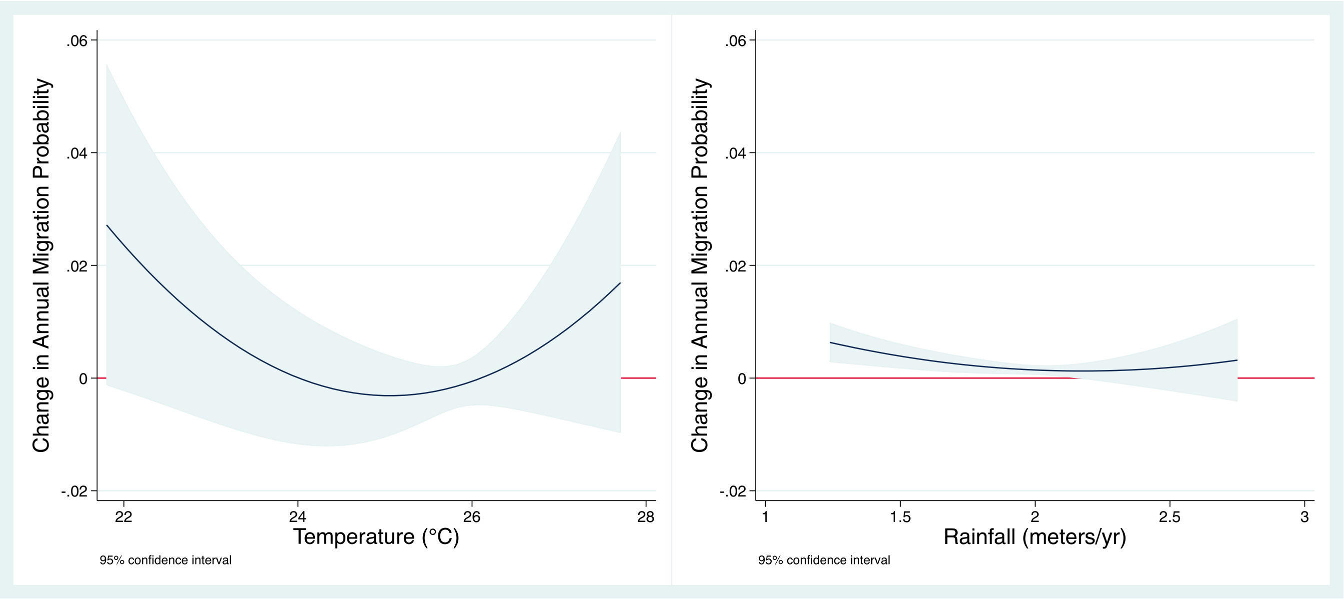

Fig. 1. Nonlinear effects of temperature and precipitation on annual migration probability.

houses destroyed by flood is estimated to reduce annual migration probability by 0.000006. We do not have data for volcanic eruptions when financial losses are used as a measure of disaster. Among the remaining measures of eruptions, however, we estimate a small positive effect of eruptions in four of six models.

Evidence for an Economic Mechanism by Which Environmental Factors Influence Migration. Of all of the environmental factors, temperature had the most significant effect on migration. There are multiple channels through which temperature can influence migration behavior. Studies establishing a negative effect of temperature on agriculture productivity (16–19) have shown, for example, that each 1 °C increase in growing-season minimum temperature in the dry season resulted in 10% decline in rice yield in Philippines (18). Similarly, each degree increase in average growing season temperature resulted in 17% decline in yields of corn and soybeans in the United States (19). Research has also shown that in response to higher temperature, economic output losses in the nonagricultural sector can even exceed losses occurring in agricultural sectors, and these losses grow nonlinearly near 25 °C (12). Furthermore, each degree increase in annual temperature has been shown to reduce annual economic growth by as much as 1.1% points (20). Temperature increases are also shown to be associated with increase in the risk of violent conflicts (21–23). A rising temperature could therefore increase outmigration through a negative effect on income in agriculture as well as nonagricultural sectors and potentially over time by creating a less stable social environment. Prior work suggests there is evidence that temperature affects migration through its influence on agricultural productivity (13–15).

We cannot consider all possible mechanisms by which the environmental variables influence migration, but we are able to examine whether the data are consistent with previously suggested economic channels. If an economic mechanism is important for explaining the dominant effect of temperature on migration, we expect temperature should have a similarly dominant influence on economic conditions. To test this notion, we estimate the effect of climate and disaster variables on the value of household assets, a proxy of household's wealth or income over time by running an empirical model that is consistent with our model specification to predict migration. However, unlike migration flows, household assets are measured for years 1993, 1997, and 2000. Therefore, though we use similar approach of predicting the effects of period-average of environmental variables as before, we have to predict the impact of different period-average of environmental variables on household assets.

Table 2 summarizes the results using two different ways in which environmental variables are measured. For example, results in the first column use environmental factors measured for the most recent 2 y (1992 and 1993, 1996 and 1997, and 1999 and 2000) to predict their effects on the value of household assets measured in 1993, 1997, and 2000, respectively. Similarly, in the second column environmental factors measured for the most recent 4 y are used.

The results in both the regressions consistently establish a significant nonlinear effect of temperature on the value of household assets. The turning point value is at 24 °C, such that below the period-average temperature of 24 °C, any increase in temperature increases household assets, but above 24 °C a rise in temperature is related to a decline in household assets. The nonlinear relationship at higher temperature is such that at 25 °C a 1 °C increase in temperature is related to a 14–15% reduction in the value of household assets, whereas at 26 °C a 1 °C increase in temperature is related to a 28–31% decline in the value of household assets. This consistently significant link between temperature and household assets suggests a potential income channel through which temperature may affect migration. The results are consistent with findings in a recent study, which showed that extreme temperature and not rainfall increased the long-term migration of men in rural Pakistan by lowering one-third of farming income and resulting in a 16% decline in nonfarm income (24).

Interestingly, we also find that landslides, the only natural disaster that had a consistent positive effect on migration, also have a significant negative effect on household assets in the second column. Each 1% increase in deaths from landslides lowers household assets by 5%. The results suggest that reduction in a household's income could be one possible mechanism via which landslides increase migration.

Projections of Temperature Effects on Migration. Based on our estimates for consistent effects of temperature on whole-household migration, probably driven in part through economic channels, we consider the potential effect of climate change on future

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Table 2. The effects of temperature, precipitation, and natural disasters on the Log value of household assets using environmental factors measured for the most recent 2 y and 4 y

Independent variables	Environmental factors measured for 2 y	Environmental factors measured for 4 y
Temperature	4.87047**	4.41603**
	(1.97275)	(1.75353)
Temperature squared	−0.10073**	−0.09124***
	(0.03938)	(0.03268)
Precipitation	0.08062	0.27600
	(0.29311)	(0.45059)
Precipitation squared	−0.01834	0.01211
	(0.07001)	(0.10459)
Earthquake	−0.00590	0.01864
	(0.02535)	(0.01830)
Eruption	0.04559	0.01816
	(0.10827)	(0.01542)
Flood	0.05721	0.00007
	(0.03481)	(0.01662)
Landslide	0.01673	−0.05054***
	(0.02579)	(0.01798)
Observations	19,398	19,398

Logarithmic transformation of measures of disasters and household asset value used. Results control for household characteristics along with province and time fixed effects. SEs (in parentheses) corrected using multidimensional clustering. $***P < 0.01$, $**P < 0.05$, $*P < 0.1$.

rates of permanent migration. Using 1960–1990 temperature as the baseline, over a period of half a century there has been a small increase of 0.2 °C in the average annual temperature of Indonesia (Fig. S2). The past (1960–2007) trend in average annual temperature of each individual province, however, shows that most of the provinces experienced an increase in temperature with only a few exceptions. For example, over the last half a century, some provinces, like East Nusa Tenggara and Central Java, experienced a greater-than-average increase in temperature compared with the country as a whole with an increase of 1.17 °C and 0.74 °C, respectively. The provincial level temperature trends elucidate how temperature changes may have already affected migration from certain provinces. In addition, our analysis of panel data shows the migration response to the highly variable period-to-period temperature, and not just the entire long-term trend in temperature.

Based on the coupled model intercomparison project phase 3 (CMIP3) model output (averaged over 21 CMIP3 models) for temperature projections, using 1960–1990 as the baseline climate, by 2100 the average annual temperature in Indonesia is projected to increase by 2 °C to 2.5 °C under the A1B emissions scenario (25). (New assessments will likely become available in the next few years based on CMIP5 model output, and our projected effects of temperature on migration should be reexamined in the context of such studies.) We adjust these temperature projections with historical data indicating a temperature increase of 0.2 °C between the 1960 and 1990 baseline temperature and the 2007 temperature. The resulting difference gives us 1.8 °C (2–0.2) to 2.3 °C (2.5–0.2) as the projected range for future increase in temperature from 2007 to 2100 for all of Indonesia. We then assume that the national average increase applies to each province and estimate the effect of the projected future rise in temperature on annual migration probability of households using our regression coefficients for temperature. This procedure inherently assumes that migration response to multiyear variations resembles that of long-term trends in temperature, an untested proposition. Also, large uncertainties in province-level temperatures result from using this approach, but it serves the purpose here of demonstrating the potential magnitude of climate-related migration for the country as a whole.

Assuming the 2007 average annual temperature of 25.1 °C for the whole country as the starting point, in the low- and high-temperature projection scenarios, the average annual temperature is projected to increase to 26.9 °C and 27.4 °C, respectively, by 2100. We apply our quadratic model for the temperature effect and assume the same temperature sensitivity of migration in the future as now. By 2100, the annual probability of whole-household migration to another province is expected to increase by 0.01–0.016 (in the low and high projected temperature scenarios respectively) compared with the annual migration probability at the 2007 average starting temperature of 25.1 °C. If the starting temperature for some provinces is higher than the average for the country, the predicted annual migration probability can be considerably higher given the nonlinear relationship between temperature and migration.

To demonstrate the above point, we include the predicted change in annual outmigration probability under the projected low- and high-temperature increase for the sampled provinces (Table S4). For provinces such as Central Java, East Java, Lampung, and South Sumatra, with a starting temperature at around 26 °C, the predicted increase in outmigration probability varies from 0.02 to 0.03, which is much higher than the predicted increase for the country as a whole at 0.01–0.016. Similarly, for provinces such as South Kalimantan, Yogyakarta, and Jakarta, with an even higher starting temperature at ∼27 °C, the predicted increase in outmigration probability is much higher ranging from 0.03 to 0.04 for the first two and 0.03 to 0.05 for Jakarta. However, provinces such as North Sumatra, South Sulawesi, and West Sumatra, with a starting temperature at ∼24 °C, are likely to see no increase in outmigration, whereas a province like West Java may experience a very small increase of close to 0.01. At the other extreme is Bali, with a starting temperature at ∼22 °C, which may actually experience a decline in outmigration probability with the predicted decline between 0.02 and 0.03.

An earlier study projects that by 2080 climate change, through its effect on agricultural productivity, may lead to additional outmigration of 2–10% of the current working age population in Mexico (13, 14). In another study using baseline climate in 1960–1989 and the expected change in weather, by 2070–2099, 5-y outmigration rates of rural counties in the US Corn Belt are projected to increase by 30% due to decline in crop yields as a consequence of warming climate (15). Although these results provide some basis of comparison for our study, the magnitude of the effects of temperature on migration may vary by location due to a host of unobservable characteristics in different country settings that cannot be fully controlled for.

Discussion

This study investigates the effects of natural disasters and climatic variations on permanent migration of households between provinces. The findings suggest that sudden disasters have much smaller impact on permanent migration relative to the strongly nonlinear effect of temperature and, to a lesser extent, precipitation. These results complement the existing findings that suggest an influential role of disasters on temporary and short-distance moves rather than permanent moves.

As for the effects of climatic variations on migration, rainfall has a quadratic effect such that in conditions that are initially dry, a decline in rainfall tends to increase migration, whereas in wetter conditions, an increase in rainfall increases migration. Although significant, these effects of rainfall on permanent migration are small in magnitude, suggesting that rainfall may have a more profound impact on temporary and shorter-distance movement as also suggested in previous literature.

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Finally, we find that at initially higher levels of temperature, permanent migration of households is influenced by a further increase in temperature, *ceteris paribus*. Our results are consistent with the theory that temperature is likely to influence migration through its impact on local economic conditions. It should be noted, however, that Indonesia's tropical climate and its high dependence on agriculture along with its strong culture of interprovincial migration (*SI Text, Internal Migration in Indonesia*) may particularly increase the effect of temperature on interprovincial migration. The finding nevertheless has significant implications for future effects of global warming on migration. For future research, the findings in this study underscore the importance of using a suite of measures of climatic factors along with a clear distinction on the type of migration when exploring the link between climatic variations and population mobility.

Materials and Methods

The primary source of data for this study is the IFLS, which is a household panel survey of 7,185 original households interviewed at wave 1 in 1993. A total of 86% were followed until wave 4, and 91.4% were followed until wave 3. Using the four waves of the IFLS measured in 1993, 1997, 2000, and 2007, we constructed records of whole-household migration flows over three time periods, creating interprovincial flows for years 1993–1997, 1997–2000, and 2000–2007 (*SI Text, Data*). Because the time intervals between the four survey waves were inconsistent, we use annual migration probability of household rather than using migration as a bivariate outcome.

Data for measures of natural disasters was derived from DesInventar database, which provides information on disasters using preexisting official data, academic records, newspaper sources, and institutional reports. Multiple measures of disasters are used to capture the intensity of disasters. The IFLS provinces, which include southern and western islands such as Java and Sumatra, fall in the regions that are most impacted by natural disasters, with mortality risks from all types of disasters mostly falling within the highest or second highest deciles (Fig. S3). Although all parts of the country experience a number of disaster events such as earthquakes, floods, landslides, volcanic eruptions, cyclones, droughts, surge, and tsunami at some levels, a closer look at the spatial variation in hazard risks from each type of disaster clearly reveals the significance of floods, volcanoes, landslides, and earthquakes (26). We therefore chose these four types of natural disasters, which pose the highest risks in the IFLS provinces in terms of their frequency as well as their intensity of impact (*SI Text, Data*). For the measures of disasters, we use the logarithmic transformation of the variables because it can help in dealing with the positively skewed distribution of the disaster measures and any bias in the results driven by extreme values (27, 28).

Finally, we introduce metrics of climatic variations using the province-level measures of average annual precipitation and average temperature derived from data provided by the University of Delaware (29). We use the monthly reconstructions of temperature and precipitation (measured on a 0.5×0.5 degree grid) by Willmott et al. (29) and take the area-weighted average over each province in each month. These monthly means are then averaged to construct mean temperature and annual mean precipitation in each period. Temperature is measured in degrees Celsius, and precipitation is measured in meters per year (*SI Text, Data* provides further description; see Table S5 for descriptive statistics).

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