Modeling equilibrium responses to climate-induced migration*

Jared C. Carbone[†] Sul-Ki Lee[‡]

February 2018

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Abstract

We construct a quantitative model to simulate the impacts of climate change on U.S. domestic migration patterns. The model combines a strategy for estimating household demand for climate amenities in the presence of migration frictions with a simple, equilibrium framework for modeling counterfactual migration responses and their implications for regional welfare, prices and populations. Our estimates suggest that migration frictions exert an important influence on equilibrium outcomes, limiting adaptation to climate through relocation and resulting in a regional pattern of winners and losers.

Keywords: climate change impacts, migration, sorting equilibrium.

*We are grateful to David Albouy, Walter Graf, Ryan Kellogg and Hendrik Wolff for supplying us with the dataset used in their study, which inspires and forms the basis of much of the work described here. We acknowledge support from the Payne Institute for Earth Resources, Colorado School of Mines and the U.S. Department of Energy Office of Science, Biological and Environmental Research Program, Integrated Assessment Research Program. All errors are our own.

[†]Division of Business and Economics, Colorado School of Mines, jcarbone@mines.edu

[‡]Division of Business and Economics, Colorado School of Mines, sulee@mines.edu

Climate is an important factor in determining where households choose to live. Leaving employment conditions aside, empirical studies of labor migration consistently find that it is among the more important explanatory variables (Kennan and Walker, 2011). Migration may, therefore, be an important behavioral response to climate change.

Climate impacts are predicted to have a strong spatial signature at both global and regional levels with changes in temperature, precipitation and frequency of extreme weather events that differ in sign and magnitude. In the United States, the focus of our analysis, the predicted temperature changes result in the South experiencing an increase in extreme heat days. In the North, the primary effect will be a reduction in extreme cold days. Proximity to oceans and other geographic features also shape the spatial pattern of predicted climate change. The changes are also non-marginal. Under the A2 scenario of IPCC (Intergovernmental Panel on Climate Change), much of the Southeast is expected to gain 50–100 days on which the average daily temperature exceeds 80 degrees Fahrenheit (°F) by 2070–99.

For the types of non-marginal adjustments in climate expected over the next century, theory predicts equilibrium adjustments in regional labor and housing markets. The in-migration experienced by locations with desirable climates should drive down wages as the local workforce supply grows and drive up rents as demand for housing rises all else equal. Equilibrium is restored when the standard of living households may expect to achieve by moving to this location falls to the point where households are indifferent between moving there and locating elsewhere (Rosen, 1974; Roback, 1982). Indeed, the hedonic method of estimating the value of local amenities is predicated on the notion that full arbitrage occurs — so that differences in equilibrium wages and housing prices across locations reflect the full value of differences in local amenities.

Thus, if the spatial gradient of climate change is sufficiently large and the costs of migration are sufficiently low, households may move to arbitrage differences in living standards, with consequences for regional populations, prices and well-being.

Nevertheless, migration frictions may be considerable at the spatial scales relevant to the study of climate change. Migration research also shows that destination distance is a strong determinant of propensity to migrate, with the large majority of moves for U.S. households occurring within one's state of birth (Kennan and Walker, 2011).

Collectively, these features of the problem have a number of implications for the study of regional climate impacts. First, substantial migration frictions would limit the extent to which households can use migration as a form of adaptation, increasing the aggregate cost of climate change relative to a world in which households may move freely to avoid its impacts. Moreover, they would raise the potential for finding important distributional consequences of climate change, producing relative losses or gains in regions that experience unfavorable or favorable changes in climate.

Second, a model that is capable of capturing the adjustments in regional prices from climate-induced migration is justified for analyzing the types of non-marginal changes in climate predicted to occur over the next century. Welfare estimates of climate impacts that fail to account for adjustments in regional price may overstate costs of climate-disadvantaged regions, for example, by assuming that adjustments in wages and rents fail to compensate households for a poorer climate. They may also fail to reflect the distribution of costs and benefits across regions to the extent that price signals and migration telegraph the consequences of local climate impacts across space.

Third, a consequence of the previous two points is that the extent to which spatial aggregation in models assessing the welfare impacts of regional climate change matters will hinge on the degree to which regional markets are integrated. If migration is relatively costless, it will ensure that quality of life is similar across locations, because households will arbitrage away the gains from especially desireable locations. In this case, it may acceptable to use spatially aggregated models to measure the aggregate welfare implications of spatially distinct climate impacts. If there are important barriers to relocation, then the results of such a model may be misleading.[1]

Conversely, a strategy for valuing climate amenities like the hedonic method — which relies on compensating price differentials — may not perform well to the extent that migration frictions drive a wedge between quality-adjusted prices across locations and bias measurement of the welfare impacts of climate change.

Finally, climate-induced migration may have important interactions with the underlying population dynamics that drive the regional distribution of people. That is, even if migration has a relatively modest contemporaneous effect on populations, these effects will be compounded over time by adding or subtracting people to the base population to which growth rates are applied. Thus, a small contemporaneous effect can become a large over the long time horizons that are relevant to the study of climate impacts. For example, suppose the natural growth rate (births minus deaths) is 2% and migration rate is 1% annually. This implies an elasticity of population fifty years in to the future with respect to a constant migration rate of approximately 2. That is, a change of the migration rate from 1% to 1.01% would cause a 2% increase in population. Extrapolating, a change to 1.1% migration rate would cause a 20% change in population.

We construct a quantitative model that estimates the impact of climate change on U.S. domestic migration patterns. It combines a strategy for estimating household demand for climate amenities in the presence of migration frictions with a simple, equilibrium framework for modeling counterfactual migration responses and their subsequent impacts on local wages and housing prices and population across the United States.

Bayer et al. (2009) was the first study to estimate migration frictions in the context of valuing a local environmental disamenity (particulate-matter (PM) air pollution). The authors formulate a discrete choice model which uses household migration decisions as the

[1]This logic is of general importance to the valuation of changes in environmental quality with strong spatial signatures. All of the criteria air pollutants, for example, would likely fit this definition. Therefore, developing a framework that would allows research to determine an appropriate level of aggregation is needed.

main source of identification, allowing them to explicitly account for migration frictions as revealed by household propensity to migrate different distances from their place of birth. Their results indicate that the marginal willingness to pay (MWTP) for improvements in PM air quality is approximately three times as large as comparable estimates based on models (using the hedonic method) that ignore this element of the problem.

A few recent studies employing either the hedonic or discrete-choice framework find that the welfare effects of the projected changes in climate amenities in the U.S. may be significant (Albouy et al., 2016; Sinha and Cropper, 2015; Fan et al., 2016, 2018). All of these studies find agreggate losses from climate change on the order 1-4% of household income.[2] Albouy et al. (2016) applies the hedonic method to valuing climate amenities, using cross-sectional variation in climate and prices. However, it does not explicitly control for the influence of migration frictions.[3] Sinha and Cropper (2015) and Fan et al. (2016) follow Bayer et al. (2009), estimating a discrete choice model to value climate amenities in the presence of migration frictions. Neither study develops an equilibrium approach to modeling migration decisions however.[4]

Fan et al. (2018) use the econometric model estimated in their earlier study to link migration responses to a computable general equilibrium (CGE) model of five US macro regions to consider how migration and regional wage feedbacks interact to determine regional welfare and economic impacts. It is, as a result, most similar among the studies in the extant

[2]Studies focusing on countries where impacts on the agricultural sector are expected to be significant also find large impacts (see, for example, Dillon et al. (2011); Mueller et al. (2014)). Finally, there is mixed evidence on international migration induced by climate change, with some finding impacts (Cattaneo and Peri (2015)) and others not (Beine and Parsons (2015)).

[3]One of the econometric specifications considered by these authors includes state fixed effects, ensuring that only within-state variation is responsible for the identification of climate amentity coefficients. This could mitigate any bias due to the influence of migration frictions. Nevertheless, the authors note that most of the identification here comes from large states, such as California and Texas, which contain a relatively wide range of climates, where climate frictions are more likely to be important.

[4]Albouy et al. (2016) briefly describe a welfare calculation in which they allow for migration at the end of Section 5, finding that it modestly reduces the welfare cost of climate change. They assume the population change is proportional to the change in their quality-of-life measure. They do not explicitly model the changes in regional housing and labor markets or migration frictions however.

literature to the analysis described here. They find both that migration has an important influence on regional economic outcomes and that wage feedbacks significantly temper equilibrium migration responses relative to a model with no such equilibrium adjustments included.

Our contribution is to consider how migration frictions and equilibrium responses together shape future regional populations, prices and well-being. Our approach differs from Fan et al. (2018) in a number of ways. First, our equilibrium model takes a more parsimonious approach to capturing price feedbacks than a detailed, multi-sector CGE model like the one used in that study. The advantage of this approach is that facilitates an exploration of the role of spatial aggregation in shaping the outcomes of interest in the presence of migration frictions. Modelling an aggregated region is equivalent to assuming perfect mobility and market integration across the subregions of which it is comprised. We explore how important this assumption is likely to be.

Second, we consider feedbacks to regional housing prices in addition to wages. Empirically, there is far more regional variation in housing prices than wages, suggesting that it is important to account for potential feedback effects from these markets as well. Knowing how much of the effects of climate change are capitalized into these different markets is important for understanding its incidence across different stakeholders.

Third, we develop population projections that incorporate the interaction between migration and underlying driver of population growth. As discussed, the compounding effects of population growth imply that impacts of on-going climate-induced migration across the century could be quite different from the effects of contemporaneous migration imposed on a future projection of population.

Our strategy for estimating household preference with respect to migration frictions and climate amenities builds on all three of these recent studies. Following Bayer et al. (2009), we estimate a discrete choice model using a combination of socio-economic variables from

IPUMS with historical climate data from Schlenker and Roberts (2009) linked at the level of a metropolitan statistical area (MSA) — the same dataset employed by Albouy et al. (2016). The discrete choice framework allows us to incorporate migration frictions in the estimation of willingness to pay for climate amenities.

We find estimates of migration frictions and climate amenities that are consistent with the earlier studies based on similar designs (Bayer et al., 2009; Sinha and Cropper, 2015; Fan et al., 2016). In particular, we find statistically significant effects of days per year in which the 24-hour average temperature exceeds $28°C$ $(86°F)$. Our central estimate of willingness to pay to avoid an extra day per year above this temperature threshold is approximately \$350. Also consistent with past studies is our finding of important sources of heterogeneity in migration frictions and climate sensitivity across households of different ages, education levels and household structures.

The equilibrium model takes the estimates produced by the household choice model as the basis of its calibration. Migration is modelled at the state level. From this baseline, we conduct counterfactual climate simulations based on the IPCC A2 scenario.

We find that state populations change by as much as 10% of baseline levels by the year 2070. Regional prices change by as much as 12%. Our simulations show pronounced regional impacts of climate change, with the Southeast and the West experiencing the largest losses.

1 Econometric model of household choice

We combine socio-economic variables from the IPUMS 2000 Decennial Census data with historical climate data from Schlenker and Roberts (2009), linked at the MSA level, to estimate demand for climate amenities in a discrete choice framework. In this respect, we build directly on the work of Albouy et al. (2016), Bayer et al. (2009), Sinha and Cropper (2015) and Fan et al. (2016).

The econometric strategy proceeds in two steps. We first estimate how households respond to wage opportunities and migration costs. All location-specific elements of choice are captured as location fixed effects. In the second step, we regress our estimated fixed effects on location characteristics — including climate characteristics.

The indirect utility function is given as:

$$u_{ik} = \ln v_{ik} = \alpha \ln w_{ik} - \ln \delta_{ik} + \ln \theta_k + H_{ik} + \epsilon_{ik}$$

where v_{ik} is indirect utility of household i in MSA k, w_{ik} is the wage that the head of household i would earn in k, δ_{ik} is the migration friction associated with household i moving to location k, θ_k is a location-specific fixed effect and ϵ_{ik} is the idiosyncratic individual preference term.

H_{ik} is a preference heterogeneity term which captures the idea that different demographic groups may differ in their climate preferences and is defined as

$$H_{ik} = \sum_{d \in \mathcal{I}_i} \sum_{n} \kappa_{dn} \ln c_{nk}$$

where d indexes the demographic dimensions of heterogeneity, $\mathcal{I}_i$ is the set of demographic categories to which household i belongs and n indexes the set of climate amenities, c_{nk}. In our base specification, we interact our climate measures of extreme heat days (days with an average temperature over a temperature threshold) and extreme cold days (days below $0°C$) with the following demographic categories: climate zone of birth and college education.

Assuming a type-I extreme value distribution (Gumbel distribution) on ϵ_{ik} gives the probability of household i choosing k:

$$\pi_{ik} = \Pr(u_{ik} > u_{ij},\ j \neq k) = \frac{\exp(u_{ik})}{\sum_j \exp(u_{ij})} = \frac{\exp(\alpha \ln \hat{w}_{ik} - \ln \delta_{ik} + \ln \theta_k + H_{ik} + \epsilon_{ik})}{\sum_j \exp(\alpha \ln \hat{w}_{ij} - \ln \delta_{ij} + \ln \theta_j + H_{ij} + \epsilon_{ij})} \tag{1}$$

Equation (1) is a conditional logit model which enables us to recover the parameters of the indirect utility function via maximum likelihood estimation. Estimating Equation (1), however, requires the following two intermediate steps: (1) wages a household head would have earned in each location that are not chosen ($\hat{w}_{ik}$) must be estimated; and (2) migration frictions (δ_{lk}) must be modelled.

In the second stage,

$$\ln \hat{\theta}_k = -\beta \ln \hat{p}_k + \gamma \ln c_k + \eta \ln X_k + \xi_k$$

where $\hat{\theta}_k$ is the first-stage fixed-effect estimates and the regressors are climate variables ($\ln c_k$), the estimated price of housing services ($\ln \hat{p}_k$), and other local characteristics ($\ln X_k$) to estimate γ and η. ξ_k is an iid error term. The price of housing services is estimated from a separate regression where the value of a house or rental payments are regressed on region fixed effects and other dwelling characteristics. The region fixed effects represent the degree to which the value of the house for homeowners or rental payments for renters — independent of dwelling characteristics — varies over MSAs.

It is possible that an unobserved economic activity in an MSA may affect local housing prices, which may bias the coefficient β. To address this concern, $\beta \ln \hat{p}_k$ term is moved to the left hand side.[5]

$$\ln \hat{\theta}_k + \beta \ln \hat{p}_k = \gamma \ln c_k + \eta X_k + \xi_k$$

[5] Rather than estimating β, we directly derive the value of the parameter from the utility function. That is, $\beta = \alpha(p_k H_i^* / w_{ik})$ where H_i^* represents the household's demand function for housing services. We use the median value of β, which is 0.239 in our analysis.

The parameters estimated from the conditional logit model for wages ($\hat{\alpha}$) and migration frictions ($\hat{\delta}_{ik}$) and fixed effects ($\hat{\theta}$) as well as the climate parameters from the from the MSA fixed effects regression ($\hat{\gamma_k}$) are used in our quantitative equilibrium model to predict future migratory responses to climate change.

1.1 Wage prediction

Although we only observe wages in the chosen locations, there are a number of households with similar characteristics in different locations in our data set, which allows us to predict wages in each location. Wages are predicted based on the following model:[6]

$$\ln w_{ik} = \psi_{0k} + \psi_{1k} WHITE_i + \psi_{2k} MALE_i + \psi_{3k} OLD_i + \sum_{m=4}^{7} \psi_{mk} EDU_{mi} + \sum_{n=8}^{30} \psi_{nk} OCC_{ni} + \epsilon_{ik}^{w} \tag{2}$$

where $WHITE_i$ and $MALE_i$ are dummy variables set to be one for white people and male, respectively; OLD_i equals 1 if the household head is older than 65 years old and 0 otherwise; EDU_{mi} is educational attainment which is either high school dropout, high school graduate, some college, or college degree; and OCC_{ni} is the type of job occupation. Among 25 occupations excluding "no occupation" in the original census data, military and extraction are eliminated because people working in those type of jobs are supposed to have restricted mobility. We run Equation (2) for each MSA since the impact of having a college degree, for instance, might vary over locations.

[6] We recognize that an omitted variable bias is likely to exist. For example, motivation might influence educational attainment as well as wage level. This means that ψ_{mk} do not precisely measure the *causal effect* of education on wages. This does not necessarily bias the wage predictions, however, as long as the bias in ψ_{mk} is consistent across individuals.

1.2 Modeling migration frictions

Following Bayer et al. (2009), we model migration frictions as a function of dummy variables reflecting distance from one's place of birth, with the obvious hypoethesis that migration frictions are increasing the further one travels from home.

$$\ln \delta_{ik} = \mu d_{ik} + \mu^{kid} d_{ik}^{kid}$$

where

$$d_{ik} = \{d_{ik}^{S}, d_{ik}^{R1}, d_{ik}^{R2}\},\ d_{ik}^{kid} = \{d_{ik}^{S,kid}, d_{ik}^{R1,kid}, d_{ik}^{R2,kid}\} \quad (3)$$

where d_{ik}^{S} equals one if k, the location a household head i is found to be residing in, is in his or her birth state. Similarly, d_{ik}^{R1} and d_{ik}^{R2} are set to be one if the household head was living in the birth census region and macro region, respectively.[7] The terms labeled "kid" indicate interaction terms that describe the differential cost of migrating for households with children.

It is important to emphasize that our conception of migration frictions is wholistic; δ_{lk} may capture financial outlays associated with moving but it may also capture non-price elements such as the psychic pain a household experiences in moving or cultural differences between origin and destination. Perhaps most importantly, it may capture locational preferences, such as home bias, whereby household tastes are shaped by the characteristics of a location other than those captured by local prices and climate amenities.

This approach to modelling frictions also motivates our choice to differentiate between households with and without children in estimation. A potentially important source of frictions for young families is dependence on family and friends for childcare, a service that

[7] Census region and macro region are defined by the U.S. Census Bureau. In the U.S., there are nine census regions (i.e., (1) New England; (2) Mid-Atlantic; (3) East North Central; (4) West North Central; (5) South Atlantic; (6) East South Central; (7) West South Central; (8) Mountain; and (9) Pacific) and four macro regions (i.e., (1) Northwest; (2) Midwest; (3) South; and (4) West).

would be difficult (or expensive) to reproduce if one moves away. Because an important part of our analysis involves projecting regional populations, we would like to know the fertility profile of migrants. Migrants with children (and young migrants) are most likely to contribute to the regional population of their destination through fertility.

1.3 Estimating price of housing services

Housing prices are estimated from the following model:

$$\ln \rho_{ik} = \ln p_k + \lambda_k \Lambda_i + \boldsymbol{\sigma_i'} \Phi + \epsilon_{ik}^p, \tag{4}$$

where ρ_{ik} is annualized housing prices for home owners and annualized rental payments for renters; Λ_i is home ownership dummy equals one if the household head owns the house; and $\boldsymbol{\sigma_i}$ is a vector of dwelling characteristics including number of rooms, number of bedrooms, age of property, acreage of property, etc. $\ln p_k$ is modelled as region fixed effects so that it represents the price of housing services in each region after controlling for home ownership premium and dwelling characteristics.

2 Data

Our data for household characteristics originate from U.S. Census 2000 (5% sample) available from Integrated Public Use Microdata Series (IPUMS). This data set provides cross-sectional individual-level information including demographic and dwelling characteristics, wages, housing prices, etc. Among the observations in the raw data set, we keep household heads only. Based on this, we assume that household heads are responsible for making residential location decisions. We also restrict our analysis to households living in the contiguous U.S. In the wage-prediction regressions, we use the full sample of household heads (approximately

1.8 million observations). In the first stage of the logit estimation, we limit the sample to a random selection of 20,000 households, to limit the computational burden of solving the maximum likelihood problem. We run the model for different age ranges of household heads: under 35 years old, 36-50 years old and 51-60 years old. We do not consider retirees, as we are using wage income as our source of variation for estimating the marginal utility of income.

The main data source for the climate variables is Albouy et al. (2016). Recent historical climate data in Albouy et al. (2016) originate from Schlenker and Roberts (2009). Temperature data is the 1970–1999 average number of days of which daily average temperature falls into each temperature bin. There are 222 bins for each 0.9°F temperature interval. Other climate variables include average precipitation, dew point, relative humidity, etc. Climate projection data are based on the A2 scenario in IPCC (Intergovernmental Panel on Climate Change) and simulations from the Community Earth System Model, v3 from the National Center for Atmostpheric Research. The average temperature across the U.S. is projected to be 7.3°F higher in 2070–2099 compared to the 1970–99 average.

MSA-level characteristics (e.g., population, per capita income, proportion of white population, per capita crime, etc.) are collected from the County and City Data Book 2000. All county-level data are aggregated to MSA-level, which is the spatial unit of this analysis. An MSA is a geographic area containing more than 50,000 people and a high degree of population density. There are 281 MSAs represented in the 2000 U.S Census. After our random sampling of 20,000 households, we are left with 261 MSAs in the first-stage dataset.

Table 1 describes our data. The first panel, demographic data, is based on each individual who earns non-zero wages. Wage variable represents wage and salary income in dollars. The second panel, mobility pattern, shows that people do not move very much — approximately 54 percent of Americans stay in a state where they were born. Climate data in the third panel are 1970–1999 population-weighted average across MSAs. The last panel, regional characteristics, summarizes region-specific characteristics.

3 Econometric results

Table 2 shows mean (column 1) and standard deviation (column 2) of the parameters estimated from each MSA-level wage regression in Equation (2). Coefficients are consistent with general beliefs — white earn more than other races, and men earn higher wages than women, for instance. Having higher educational degree is associated with higher wages, and some occupations have higher wage levels than others do.

Coefficients for each dwelling characteristics in the price of housing service regression is reported in Table 3. Annualized value of house or annual rental payments are proportional to number of rooms, number of bedrooms, and acreage of the property, while disproportional to age of the structure. The absence of kitchen or plumbing facilities results in lower values/rents of a house. Although we do not report the estimates for region fixed effects, which is the price of housing services in our indirect utility function (p_k), the results generally make sense. For example, top five cities in terms of estimated price of housing service are San Francisco, CA; Santa Cruze, CA; Salinas, CA; New York, NY; and Boston, MA. Cities with lowest price of housing services are Gadsden, AL; Johnstown, PA; Florence, AL; Alexandria, LA; and Danville, VA.

Results of the conditional logit regression reveal that the α parameter from the indirect utility function is statistically significant for households under 35 but not for older households (Table 4). This result is in line with the notion that younger households are more driven by job opportunities in their decision to relocate.

Table 4 reports that migration frictions increase at a decreasing rate as one leaves one's birth state, census region and macro region. Compared to the estimate for marginal utility of wage, households seem to have fairly high utility costs for migration. The estimates for the

MSA fixed effects (not shown in the table) generally make sense. For example, the city with the highest value of the fixed effects estimate in our analysis (i.e., the most attractive city) is New York, NY, while Jackson, MI is the least attractive. The preference heterogeneity terms are themselves statistically insignificant but play an important role in recovering the mean estimates of climate preferences in the second-stage regression.

Tables 5 and 6 report the results of the second-stage regressions in which we attempt to separately identify the impacts of location-specific amenities. The former reports regressions run by age group and the latter reports regressions run with different temperature thresholds. All of the controls are included in the table with the exception of climate-zone fixed effects. We use USDA plant-hardiness zones to define these fixed effects. Thus our climate-amenity coefficient are identified off of within-zone variation in climate.

Among the climate variables included in the regression, we find that the coefficients on the variable indicating the number of days per year on which the daily mean temperature exceeds a high threshold ("Hot days") are most consistently significant. Dislike of higher levels of relative humidity also finds some support in the data. Older households express a greater dislike for high temperatures. We also find that when we increase the threshold for the high-temperature variable, its coefficient becomes more strongly negative.

We can use the coefficient estimates on wages from the first stage and the higher-temperature coefficient from the second stage to calculate the marginal willingness to pay (MWTP) to avoid an additional day above the temperature threshold.[8] Households 35 and under would be willing to pay approximately $350.

[8] We can calculate the MWTP for amenity n as $MWTP_n = \frac{\partial u_{ik}}{\partial c_k} \frac{\partial \hat{w}_{ik}}{\partial u_{ik}} \hat{w}_{ik}$

4 Equilibrium model

Household choice in the equilibrium model follows from the specification used in our econometric analysis. Households of type i maximize well-being, v, by choosing whether or not to move to destination k. Household well-being depends on consumption of a numeraire good, housing and an index of climate desireability, c_k. The numeraire good is internationally traded and offered at a constant price normalized to unity. Households are renters and purchase housing on local housing markets at the price of housing services, p_k. They finance their consumption out of wage income, earned by supplying a single unit of labor to the local labor market at wage rate for individual of type i, w_{ik}. The choice of the numeraire implies that wages and housing prices are measured relative to the cost of the consumption good. Based on this, utility for a household i moving to k can be written as:

$$u_{ik} = \ln v_{ik} = \hat{\alpha} \ln w_{ik} - \ln \hat{\delta}_{ik} + \ln \tilde{\theta}_k - \hat{\beta} \ln p_k + \hat{\gamma} \ln c_k + \epsilon_{ik} \tag{5}$$

where $\hat{\alpha}$, $\hat{\delta}$, $\hat{\beta}$ and $\hat{\gamma}$ represent the point estimates of the corresponding parameters from our econometric model. $\tilde{\theta}$ is the mean utility of a location after removing the influences of climate amenities and housing cost.

$$\ln \tilde{\theta}_k = \ln \hat{\theta}_k + \hat{\beta} \ln \hat{p}_k - \hat{\gamma} \ln c_k$$

We assume that a individual's expected wage is proportional to a common wage level at location k, which is determined in the equilibrium of the model, and the demographic-specific estimate of the individual from the wage regression, $w_{ik} = \hat{w}_{ik} w_k$.

Because it was the most consistently identified climate amenity in the econometric model, we include only the influence of days over a high temperature threshold in the equilibrium model. In our base case scenario, we set this threshold equal to $28°C$. Because we found no statistically significant effects, we also exclude the first-stage preference heterogeneity terms in the utility function.

We assume that ϵ_{ik}, the idiosyncractic tast shifters, are distributed iid Type-I extreme value. Therefore, the probability that a household from i migrates to k takes the multinomial logit form:

$$\pi_{ik} = Prob(u_{ik} > u_{ij},\ j \neq k) = \frac{\exp(u_{ik})}{\sum_j \exp(u_{ij})} \tag{6}$$

The law of large numbers implies that π_{ik} also represents the share of households of type i who are expected to migrate to k. Thus, the total flow of migrants from l to k, M_{lk}, can be written as

$$M_{lk} = \sum_{i \in \mathcal{B}_l} \pi_{ik} N_{0i}$$

where $\mathcal{B}_l$ represents the set of individuals born at location l and N_{0i} is the benchmark population of individuals of type i represented in the data. The equilibrium population at k, therefore, is $N^k = \sum_l M_{lk}$.

We assume that each household offers one unit of labor inelastically to the local labor market. Therefore, total labor supply in location k is also given by N^k. Using the definition of the utility function (5) and the definition of the migration share (6), we can write the labor market clearance condition as for location k as

$$\sum_l M_{lk} \geq N_0^k w_k^{\eta_k} \ \perp \ w_k \geq 0 \tag{7}$$

where η_k is the own-price labor demand elasticity and N_0^k is the benchmark population represented in the data used to calibrate the initial equilibrium in the model. The "$\perp$" symbol indicates a complementary slackness relationship between the model equation and the associated model variable (w_k here) and its non-negativity constraint. The left hand side of the equation represents labor supply and the right hand side labor demand.

w_k is normalized to unity in the benchmark equilibrium. Thus, labor demand is equal to N_o^k and $w_{ik} = \hat{w}_{ik}$ in the benchmark equilibrium. Similarly, we normalize the price of housing services in the equilibrium model such that $p_k = \hat{p}_k$. As a result, π_{ik} is equal to the predicted share of individuals choosing location k from the solution to the logit estimation problem. Therefore, the equilibrium model reproduces the benchmark location choices.

One household's demand function for housing, h_{ik}, follows from applying Roy's identity to (5).

$$h_{ik} \equiv -\frac{\partial v_{ik}/\partial p_k}{\partial v_{ik}/\partial w_{ik}} = \frac{\hat{\beta} w_{ik}}{\hat{\alpha} p_k}$$

The market clearance condition for the housing market at location k, therefore, is

$$h_{0k} N_0^k \left(\frac{p_k}{\hat{p}_k}\right)^{\nu_k} \geq \sum_l \sum_{i \in \mathcal{B}_l} h_{ik} \pi_{ik} N_{0i} \;\perp\; p_k \geq 0 \tag{8}$$

where h_{0k} is the benchmark per capita demand for housing, and ν_k the own-price elasticity of housing supply at location k. The left hand side of the equation represents housing supply and the right hand side housing demand.

The complete model consists of equations (3), (7) and (8). The model is solved as mixed complementarity problem using the PATH algorithm included with the GAMS numerical optimization software package.

All preference and migration-friction parameters are populated using point estimates from the econometric analysis. However, we must also choose values for the housing-supply and labor demand elasticity parameters. We, somewhat arbitrarily, choose these parameters to equal 2 and -2 respectively. There is little empirical guidance on reasonable values for these elasticities at the state level.

5 Climate change scenario

We follow Albouy et al. (2016) by employing projected changes in regional climate produced by the third release of the Community Climate System Model under the Intergovernmental Panel on Climate Change Assessment Report 4 (IPCC AR4) under the A2 scenario (IPCC , Intergovernmental Panel on Climate Change) for the years 2070-99. Our climate amenity is based on the average number of days per year that the average daily temperature falls above $28°C$.

Respectively, Figures 1 and 2 depict the current level of climate amenities for these temperature ranges and the predicted change in days falling into each category. The current-climate estimates are based on historical average temperatures from 1970-99. Darker colors indicate larger increases in days above the temperature threshold.

The A2 scenario predicts sizeable changes in climate in the U.S. and significant differences in the quality of the changes across regions. Northern states — particularly in the Pacific Northwest, New England and the Mountain West — gain the fewest hot days (less than 10 per year). The Southeast and parts of the Mountain West experience the most dramatic increase in hot days, with greater than 40 additional days per year. Florida is the most heavily impacted state with an 88 additional hot days.

6 Baseline results

Here we describe the main findings from our equilibrium simulation exercise. In what follows, we examine the impacts of climate change on regional populations, prices and welfare.

It is important to note that our results are intended to give an indication of the changes in our key outcomes that are due to the spatial pattern of amenity values of climate that are expected to occur as a result of climate change. There are, of course, many other factors that drive changes in population centers, prices and well-being in the present and future. For example, many of the fastest growing cities in the U.S. lie within the Southeast — an area that is projected to experience the most serious deterioration in climate. Thus, our finding that population declines as a result of this change in this region of the country should not be interpretted as a statement the overall rate of growth that may be expected in this region. Rather, it should be viewed as a prediction of growth relative to a world in which climate change does not occur.

6.1 Migration flows and population

Figure 3 shows the predicted end-of-century changes in bilateral net migration flows between nine of the most heavily impacts states. All other states are aggregated into a single "Other" region in the diagram. The colored arrows in the diagram describe the change in the number of migrants between pairs of states, measured in 100,000 migrants per year.

As expected, Florida, which experiences the largest increase in hot days under our climate scenario, is the largest source of out-migration. It is expected to lose over 350,000 residents per year. Approximately half of Florida's migrants are destined for other states in the South Atlantic region, including Georgia, Maryland and Virginia. This reflects the influence of migration frictions in the model; it is less costly for a household to undertake a regional move than a national move. Florida's migrants move in smaller numbers to states further up the eastern seaboard, to other large states and states that represent the largest improvement in climate amenities relative to their home state. These destinations include New York, New England and the Pacific Northwest.

While Georgia receives many migrants from Florida, it is on net a source of out-migration, losing approximately 80,000 residents per year, mostly to adjacent states in the South Atlantic.

In the West, California and Utah are the main sources of out-migration. California sends its migrants to Washington and Oregon. Utah sends its migrants to states with more favorable climates in the Mountain West.

Figure 4 shows the projected change in state population levels (in 100,000s of people) between 2020 and 2070. To create these projections, we start with baseline projections of state population from 2000-2030 produced by the U.S. Census Bureau. We take the population growth rates from the 2025-2030 period in the Census projections, assume that they linearly decline to 0 by 2099 and use these growth rates to interpolate values for state populations from 2035-2070. We then linearly interpolate the 2070-2099 changes in climate from the A2 climate scenario and apply it at 5-year intervals to our equilibrium migration model. The resulting migration flows are added to the baseline population and the assumed state growth rates are applied to generate the counterfactual population levels for the next time step. The series in Figure 4 shows the difference between the baseline population projection derived from the U.S. Census Bureau numbers and our counterfactual populations. Again, we focus on nine large states that heavily impacted — directly or indirectly — under our climate scenario.

Following from the changes in migration patterns, we find that Florida experiences the largest loss of population over the next fifty years, losing approximately 4 million people by 2070. Georgia, Utah and California all lose between 500,000 and 800,000 people. Washington gains the most population, adding approximately 1.2 million residents. Massachusetts, Maryland, Virginia and New York all gain between 600,000 and 900,000 residents.

Figure 5 shows the same propulation trajectories as percentage changes from the baseline population trajectories. Florida loses approximately 8% of its baseline population by 2070. Utah loses the most population in percentage terms at approximately 10% while Massachusetts gains the most at 12%.

It is worth emphasizing the relationship between migration flows and the underlying growth trajectories of different states in producing the population trajectories described in the figure. Florida and Utah are fasting-growing states under the Census Bureau's projection. When out-migration occurs under the climate scenario, their large growth rates are applied to a smaller base which results in a faster decline in population than would occur in a comparable state with a smaller growth rate. A related point is that the cumulative effects of climate-induced migration over the century are considerably larger than the contemporaneous effects due to the compounding effect of population growth over a long time horizon.

6.2 Wages, rents and quality of life

Figures 6, 7 and 8 show the counterfactual changes in state prices produced by the model. Figure 7 and 8 show percentage changes in wages and housing prices relative to a benchmark, no-climate-change scenario. Figure 6 summarizes the net effect of these price changes by calculating the change in a quality-of-life index defined as $\Delta qol = (\Delta\%w - \Delta\%p)$, where w is the local wage rate and p is the local housing price. In the figures, more positive values are depicted in darker shades of blue and more negative values in darker shades of red.

By construction, regions that experience migration inflows (outflows) will experience lower (higher) wages and higher (lower) housing prices. As a result, these same regions will register a lower (higher) value for Δqol. The logic behind this is that residents regions that experience adverse climate change will require higher wages and/or lower cost of living in order to maintain their pre-climate-change standard of living. Otherwise, out-migration will occur. Thus, the most adversely affected states will have the largest increase in Δqol.

Turning to the figures, we see that Florida sees the largest increase in wages and Δqol and the largest decrease in the housing price, reflecting the damage from climate change. Wage go up by approximately 12% while housing prices fall by approximately 4%. The fact that more of the impact of climate change is capitalized into wages that into housing prices is a mechanical effect of the model structure. The functional form we selected (and which is used by all researchers working in this literature) for the household's utility function in the econometric model implies unitary income elasticities for all demand arguments. When wages rise — as in the case of Florida — income rises. Thus, per capita demand for housing increases. This shifts up the aggregate housing demand curve and raises the equilibrium price of housing. This partially offsets the negative influence of climate.

Naturally, the largest increases in Δqol occur in the Southeast and West whicle the largest decreases occur in the Pacific Northwest and New England. While these latter regions experience some adverse climate change, the in-migration from other parts of the country more than offset these influences on prices; higher demand for housing by migrants drives its price up and the surplus of workers drives local wages down. The largest reductions in wages in these regions are on the order of 6% while the largest increases in home prices are approximately 2%. The prices effects in in-migration states tend to have be of smaller magnitude as the region of in-migration is more diffuse than that of out-migration.

6.3 Role of migration frictions

One of the motivations for our experiments is to examine the role that migration frictions play in shaping equilibrium responses to climate change. Here we report on the results of an experiment in which we remove migration frictions from the model and re-run our counterfactual experiment.

A challenge presented by this experiment is that changing the migration frictions will induce a change in the benchmark equilibrium because household will move to arbitrage differences in quality of life now that barriers to migration have been removed. Thus, we first solve for this new equilibrium and then conduct our counterfactual climate experiment off of this new baseline.

Figure 9 shows the equilibrium change in the quality-of-life index for the costless migration experiment. The spatial pattern of adjustments is similar to the one produced by our baseline model. However, the magnitude of the capitalization effects is significantly larger. For example, Florida, the state most heavily impacted by the direct effects of climate change, registers a change in the QOL index of approximately 24 as opposed to 16 under the baseline scenario. Thus, there is approximately 50% greater capitalization of the welfare impacts when migration is costless.

Theory predicts that full capitalization should occur if there are no barriers to migration and the impacts is small relative to the study area. While the latter assumption is unlikely to hold under our climate scenario, we have enforced the first assumption by design. As a result, the change in the QOL should give us a lower bound on the fully-capitalized impact. The fact that these changes are significantly larger in the costless-migration case suggests that migration frictions play an important role in shaping the welfare impacts of climate change. That is, limits to mobility shape the degree to which household can use migration as a form of adaptation. As a consequence, regions that experience the largest direct impacts of climate change also experience significantly greater damages relative to other regions.

7 Conclusion

We construct a quantitative model that estimates the impact of climate change on U.S. domestic migration patterns, combining a strategy for estimating household demand for climate amenities in the presence of migration frictions with a simple, equilibrium framework for modeling counterfactual migration responses and their subsequent impacts on local wages and housing prices across the United States.

We find that migration responses that result in changes in state populations of up to

10% of baseline levels in 2070. This is driven primarily by out-migration from the Southeast and West and in-migration to New England and the Pacific Northwest. This results in significantly higher wages (up to 12%) and lower housing prices (as low as -4%) in regions that experience out-migration. In-migration regions see the mirror images effect, but with smaller magnitudes as the region of in-migration is more diffuse than that of out-migration. Finally, removing migration frictions from the model would increase the magnitude of these capitalization effects by as much as 50%, suggesting that barriers to migration are an important force in shaping regional well-being.

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8 Tables

Table 1: Descriptive Statistics

	Mean	S.D.	p10	p90
Demographic data (Source: U.S Census 2000 5% sample)				
Age	39.13	13.62	21.00	57.00
Wage (USD)	33,153.91	40,086.36	4,000.00	65,000.00
White	0.77	0.42		
Male	0.52	0.50		
Education				
High school graduate	0.26	0.44		
High school dropout	0.15	0.36		
Some college	0.32	0.47		
College graduate	0.27	0.44		
Mobility pattern (Source: U.S Census 2000 5% sample)				
People who have moved to outside of their				
birth state	0.46	0.50		
birth census region	0.38	0.49		
birth macro region	0.33	0.47		
Climate data (Source: Albouy et al. (2016))				
Number of days in a year for which average temperature is				
0–45°F	98.67	57.25	18.53	166.12
45–70°F	165.74	31.05	141.17	181.13
70–95°F	99.38	59.40	32.73	175.41
Distance from Sea (miles)	302.01	277.17	8.51	751.90
Distance from Great Lake (miles)	712.43	640.13	74.03	1,879.67
Average land slope (degrees)	1.59	1.97	0.19	4.12
Average dew point (°F)	44.28	8.70	34.39	57.08
Average annual precipitation (inches)	481.05	167.92	204.35	672.97
Average annual relative humidity (%)	64.26	7.94	53.46	70.99
Regional characteristics (Source: City and County Data Book 2000)				
Number of manufacturing establishments	1,044.22	2,401.66	121.00	2,401.00
Local government expenditure per capita (1,000 USD)	5.25	1.90	3.66	7.51
Fraction of local tax revenue from property taxes	0.74	0.16	0.54	0.94
Per capita crime rate	0.04	0.02	0.03	0.06

Table 2: Results of Income Regression

Dep.Var = log(wage)	(1) Mean of Parameter Estimates	(2) Standard Deviation of Estimates
Individual Characteristics		
White	0.1369	0.0847
Male	0.4076	0.0656
High School Dropout	8.7528	0.4865
High School Graduate	9.3698	0.4528
Some College	9.3729	0.4996
College Graduate	9.8653	0.4554
Occupations		
Management	0.5790	0.4885
Business operations	0.3628	0.4747
Financial	0.3263	0.4744
Computer and mathematical	0.3610	0.5038
Architecture and engineering	0.4218	0.4719
Life physical and social science	0.1568	0.4659
Community and social services	-0.0213	0.4601
Legal	0.4443	0.4811
Education training and library	0.1321	0.4588
Arts, design, entertainment, sports and media	-0.2534	0.5121
Healthcare practitioners and technical	0.4824	0.4576
Healthcare support	-0.0762	0.4621
Protective service	0.0691	0.4839
Food preparation and serving	-0.7012	0.4684
Building and grounds cleaning and maintenance	-0.3363	0.4728
Personal care and service	-0.5982	0.4892
Sales	-0.1722	0.4685
Office and administrative support	-0.0184	0.4617
Farming, fishing and forestry	-0.4329	0.4625
Construction workers	0.1614	0.4697
Transportation and material moving	-0.0237	0.4591
Installation maintenance and repair	0.2931	0.4708
Production	0.2327	0.4777

Table 3: Results of Housing Prices Regression

VARIABLES	Estimates	Standard Error
Number of rooms (left out category is 1 room)		
2	0.076***	0.004
3	0.108***	0.004
4	0.111***	0.004
5	0.190***	0.004
6	0.312***	0.005
7	0.451***	0.005
8	0.582***	0.005
9+	0.803***	0.005
Number of bedrooms (left out category is no bedroom)		
1	0.035***	0.004
2	0.114***	0.004
3	0.159***	0.004
4	0.229***	0.004
5+	0.300***	0.004
Age of structure (left out category is 51+ years old)		
0–1 year old	0.474***	0.002
2–5 years	0.420***	0.001
6–10 years	0.335***	0.001
11–20 years	0.220***	0.001
21–30 years	0.107***	0.001
31–40 years	0.059***	0.001
41–50 years	0.029***	0.001
Acreage of property (left out category is less than 1 acre)		
1–9 acres	0.199***	0.001
10+ acres	0.392***	0.002
No kitchen	-0.138***	0.005
No plumbing facilities	-0.143***	0.005
Units in structure (left out category is mobile home or trailer)		
Boat, tent, van, other	-0.072***	0.011
1-family house, detached	1.133***	0.002
1-family house, attached	0.994***	0.002
2-family building	1.086***	0.002
3–4 family building	1.081***	0.002
5–9 family building	1.084***	0.002
10–19 family building	1.118***	0.002
20–49 family building	1.118***	0.002
50+ family building	1.167***	0.002
Constant	6.894***	0.021
Observations	2,855,392	
R-squared	0.496	

Standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Table 4: Results of conditional logit regression: wages and migration costs

	(1)	(2)	(3)
$\hat{w}_{ik}$	0.279***	0.055	-0.019
d^{S}	-2.619***	-2.512***	-2.467***
d^{R1}	-1.009***	-1.023***	-1.034***
d^{R2}	-0.636***	-0.499***	-0.403***
$d^{S,kid}$	-0.277***	-0.039	0.099*
$d^{R1,kid}$	-0.209**	-0.101	-0.211***
$d^{R2,kid}$	—	-0.047	0.077
Age	35	50	60

*** p<0.01, ** p<0.05, * p<0.1

Table 5: Results of 2nd-stage by age

	(1)	(2)	(3)
Cold days	0.0020	0.0042	0.0029
Hot days	-0.0065**	-0.0104***	-0.0089***
Precipitation	0.3240*	0.3127*	0.2138
Relative humidity	-0.6313	-1.3140**	-1.0959
Sunshine	-0.1324	-0.1489	0.6955
Inverse distance from sea	-1.4503*	-0.7661	-0.4736
Inverse distance from sea (squared)	0.7170*	0.4185	0.2954
Inverse distance from lake	-2.3994**	-2.7626**	-2.4991**
Inverse distance from lake (squared)	1.1393**	1.3136**	1.2062**
Slope	0.1237**	0.0588	0.0123
Population	0.8935***	0.6808***	0.6247***
Manufacturing est.	0.0166	0.2267	0.2848*
Gvt. expenditure	-0.0865	0.0806	0.0632
Property tax rates	0.1187	0.3740**	0.4167**
Income	0.0361	0.3844	0.2942
Percentage of White	0.1227	-0.0874	0.6008*
Crime rates	-0.0344	-0.0668	-0.0864
Observations	261	261	260
R-squared	0.754	0.795	0.788
Age	35	50	60
Hot temp	28	28	28

*** $p<0.01$, ** $p<0.05$, * $p<0.1$

Table 6: Results of 2nd-stage by temperature threshold

	(1)	(2)	(3)
Cold days	0.0048*	0.0042	0.0065**
Hot days	-0.0035*	-0.0104***	-0.0146***
Precipitation	0.3745**	0.3127*	0.3156*
Relative humidity	-1.4715**	-1.3140**	-1.6325**
Sunshine	-0.3853	-0.1489	-0.3113
Inverse distance from sea	-0.6815	-0.7661	-0.6137
Inverse distance from sea (squared)	0.3825	0.4185	0.3436
Inverse distance from lake	-2.6750**	-2.7626**	-2.5621**
Inverse distance from lake (squared)	1.2745**	1.3136**	1.2237**
Slope	0.0796	0.0588	0.0866
Population	0.5902***	0.6808***	0.6821***
Manufacturing est.	0.2909*	0.2267	0.2243
Gvt. expenditure	0.1111	0.0806	0.0918
Property tax rates	0.3320*	0.3740**	0.3809**
Income	0.5068*	0.3844	0.3755
Percentage of White	-0.2105	-0.0874	-0.1072
Crime rates	-0.0709	-0.0668	-0.0607
Observations	261	261	261
R-squared	0.797	0.795	0.788
Age	50	50	50
Hot temp	26	28	30

*** p<0.01, ** p<0.05, * p<0.1

9 Figures

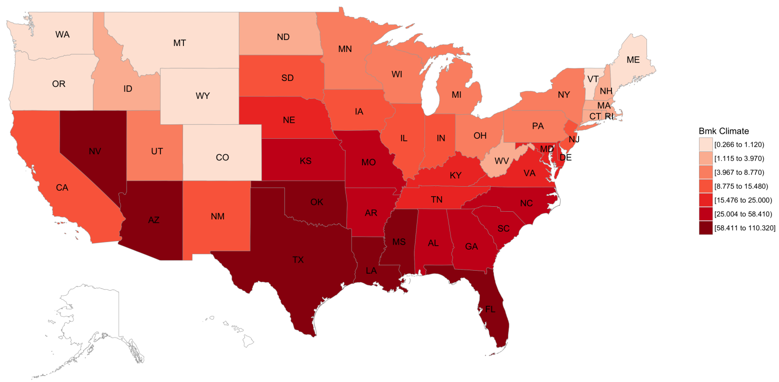


Figure 1: Historical frequency of daily average temperatures above 28°C

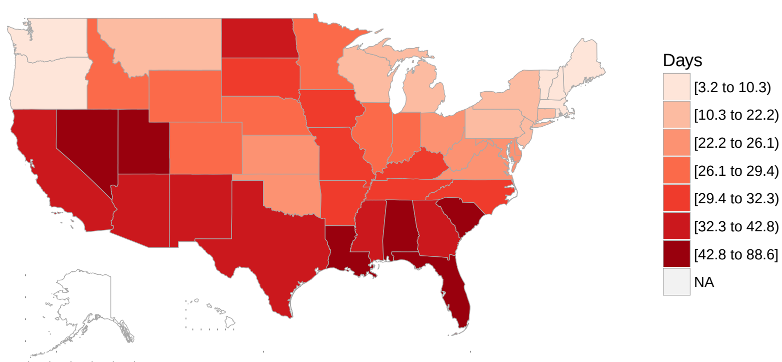
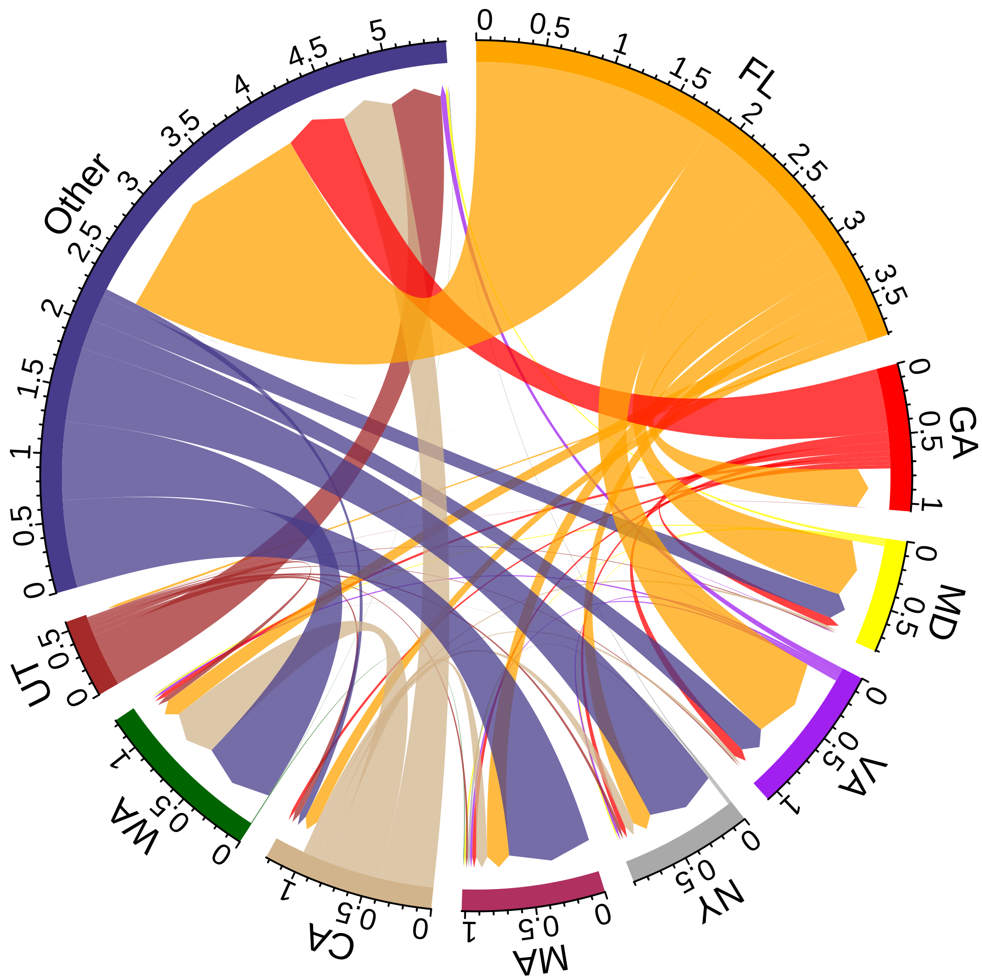


Figure 2: Predicted change in frequency of daily average temperatures above 28°C, 2070-2099



Net change in migration flows by state, numbers are reported in 100K people.

Figure 3: Net change in bilateral migration flows, 2070-2099 — 100,000 migrants per year

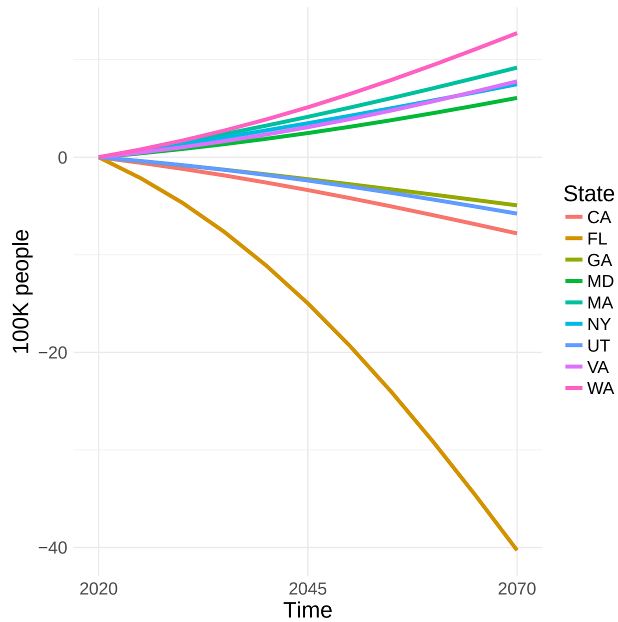


Figure 4: Change in State population, 2020-2070 — 100,000 residents

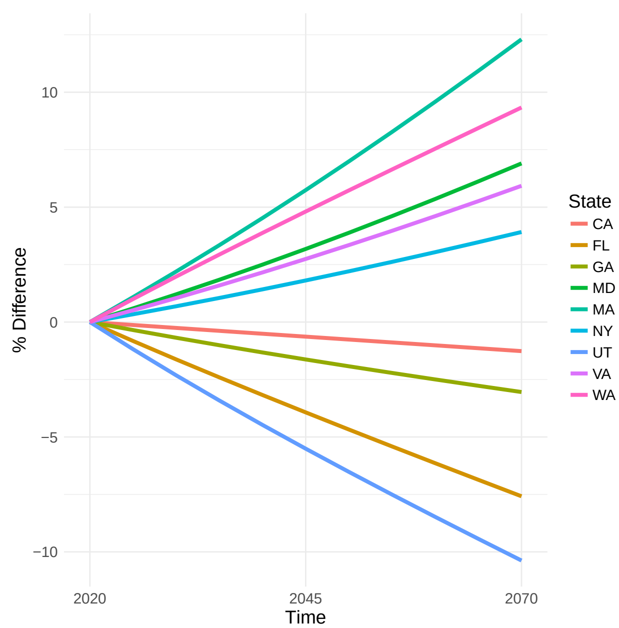


Figure 5: % change in state population from baseline projection, 2020-2070

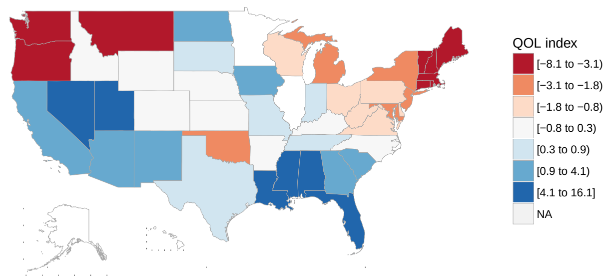


Figure 6: % change in quality-of-life index, 2070-2099

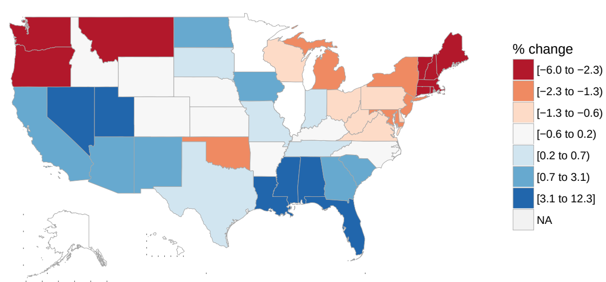


Figure 7: % change in wage, 2070-2099

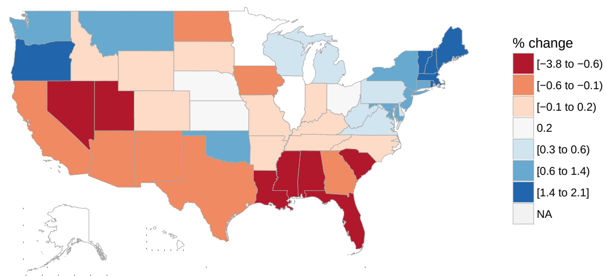


Figure 8: % change in housing price, 2070-2099

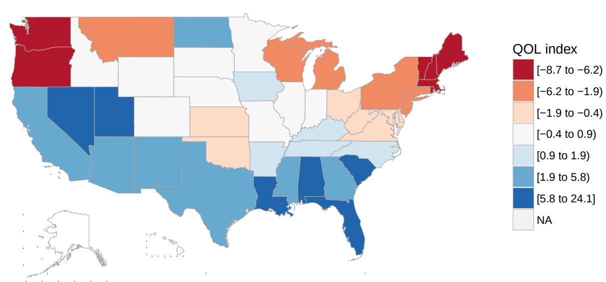


Figure 9: % change in quality-of-life index, 2070-2099: costless migration