Heterogeneity and Market Adaptation to Climate Change in Dynamic-Spatial Equilibrium

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Abstract

Climate change is expected to significantly affect the planet, but the ultimate economic impact depends on the structure of the economy and the extent to which markets can adapt to changes in local climatic conditions. Here we develop a dynamic-spatial multi-industry climate-economy model with several novel forms of heterogeneity. In our model, regions are linked through trade and factor markets, and daily temperature affects productivity growth and local amenities. We first demonstrate how to use equilibrium conditions of the model to estimate climate impacts on growth and amenities accounting for dynamic and spatial behavior. With a focus on the United States, we then simulate our model to quantify the value of adaptation through inter-state migration or by changing workers' industry of employment, which alter production patterns and trade. We find that market adaptation mitigates and even reverses the negative effects of climate change in the US. In total, market-based adaptation improves US welfare by 14 percentage points. Heterogeneity in industrial responses to climate change and within-year temperature variability play a central role in welfare and the benefits of adaptation. Heterogeneous industrial responses make climate change more beneficial by magnifying the benefits of trade and industry switching. Differences in temperature variability across space and time worsen welfare, and depress the value of adaptation through trade, migration, and industry switching. Our findings point to the importance of proper representation of industrial and climatic heterogeneity for quantifying the impacts of climate change and market-based adaptation.

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1 Introduction

In this paper we analyze the economic effects of climate change and the role of market-based adaptation. We develop a dynamic-spatial multi-industry general equilibrium model where the distribution of local daily temperature affects industry-specific productivity growth, and directly affects household utility through local amenities. In our model, forward-looking workers can adapt to climate change by changing their industry of employment, and in the US, through inter-state migration.[1] We first couple the dynamic-spatial equilibrium conditions of the model with data on trade and migration flows to estimate the effect of climate change on productivity growth and local amenities. We then use these estimates to simulate our model and quantify the historical effects of changes in daily temperature distributions during 2000–2014, as well as expected future changes through 2100. We provide new techniques for decomposing the quantitative importance of different market adaptation mechanisms, show that market-based adaptation has large welfare effects, and demonstrate that the impacts of climate change and market-based adaptation hinge upon novel economic and climatic heterogeneity that we introduce in this paper.

To gain intuition for the interaction between adaptation and heterogeneity, consider an example with two symmetric locations, home and foreign, with two industries each, manufacturing and agriculture. There is trade between locations, and workers can migrate and change their industry of employment. Suppose this world is subject to a productivity-altering change in climate. If all location-industry pairs suffer homogeneous impacts, there is no relative change in wages, and no benefit to workers from migrating or changing their industry. Now suppose the productivity effects are the same on average, but heterogeneous across locations and industries such that home suffers greater productivity losses than foreign, and agriculture is worse off than manufacturing. Relative declines in productivity in home and agriculture depress wages and induce workers to migrate to foreign and work in manufacturing. Agricultural production then shifts to foreign because of its higher productivity and greater quantity of labor, and home begins importing more agricultural products. Market-based adaptation through migration, industry switching, and trade allows workers and the economy to reallocate effort and resources to their most productive use. The extent to which market forces allow workers to mitigate the negative effects of climate shocks in this example depends on heterogeneity across industries in their productivity responses to climate change, as well as heterogeneity across locations in the extent of climate change. Proper representations of economic and climatic heterogeneity will therefore be crucial for understanding the impacts of climate change and market-based adaptation.[2]

Our theoretical framework builds on the dynamic multi-industry trade model by Caliendo, Dvorkin and Parro (2019), where locations are spatially linked through trade as in Eaton and Kortum (2002), and households are dynamic decision makers as in Artuc, Chaudhuri and McLaren

[1] The restriction of migration to the US is due to data limitations in other countries. Data limitations also restrict us to assume free mobility across industries outside the US.

[2] Unlike market-based adaptation through trade and the labor market, heterogeneity is not required to induce adaptive capital investments like air conditioning installation in factories or seawalls around coastal cities.

(2010). In our model, changes in the climate heterogeneously affect productivity growth across industries, and also directly impact the utility of households through local amenities. Our representation of the climate captures the full distribution of daily temperature in each year, which allows us to fully account for the impacts of within-year extreme temperatures and temperature variability.

Our primary empirical contribution is that we use the macro-structure of our model to develop new approaches for estimating the productivity and utility effects of climate change in dynamic-spatial equilibrium.[3] Our approach for estimating the effect of climate change on productivity growth exploits variation in bilateral trade flows across countries relative to own industry expenditures. The normalization of expenditures on goods from another country by own-expenditures eliminates bias caused by correlated spatial patterns in temperature shocks and multi-lateral trade effects.[4] The presence of spatially correlated productivity shocks confounds identification of productivity effects using variation in bilateral expenditures alone, or variation in GDP growth. This channel for bias only reveals itself in a spatial equilibrium model.

Our estimates indicate that the aggregate productivity growth response function has a robust, non-linear relationship with daily temperature and that both extreme hot and extreme cold days reduce growth relative to moderate days. Replacing a single day of the year at the optimal productivity growth temperature of 14°C with an extreme cold or hot day at -6°C or 34°C reduces productivity growth by 0.2 percentage points. Alternatively, replacing two days at the optimal temperature with one extreme cold day and one extreme hot day — a mean-preserving increase in the variance — decreases growth by 0.4 percentage points. We also estimate industry-specific response functions and find substantial heterogeneity in climate impacts across industries.

We estimate the effect of climate change on local amenities and flow utility with a fixed effects transformation of the household Euler equation. This specification identifies effects on amenities using variation in migration flows, wages, and distributions of daily temperature across locations. We find that the amenity response function is decreasing and concave in daily temperature such that replacing a single day at 14°C with a hot day at 34°C results in a decline in welfare of 1.5%.[5]

With the estimated response functions in hand, we simulate the economic effects of climate change and market-based adaptation by expanding upon the dynamic hat algebra technique introduced in Caliendo et al. (2019). We use the simulations to generate three sets of results. First, we compute the past and expected future impacts of climate change on migration and employment within the US, as well as welfare for all countries and US states. Second, we show that capturing certain real world features often missing in quantitative economic evaluations of climate change – input-output loops from use of intermediates, industry heterogeneity, amenities, and within-year temperature variability – are first-order factors for welfare and other outcomes. Finally, we decom-

[3]See Auffhammer (2018) and Kolstad and Moore (2020) for reviews of common approaches.

[4]Our specification is similar to that of Jones and Olken (2010), however they do not normalize by own expenditures. Without this normalization step, bilateral expenditures is a function of a term commonly called market access which is a non-linear function of all countries' productivities and climates. Section B.3 in the Appendix demonstrates how standard approaches are confounded by spatial linkages.

[5]And similarly to productivity growth, a mean-preserving increase in the variance decreases welfare.

pose the role of market adaptation to climate change, and how it interacts industrial and climatic heterogeneity, using a newly developed set of quantitative techniques. These techniques can be used to analyze the role of adaptation through labor markets and trade in response to a change in any exogenous economic fundamental.

We find that climate shocks over 2000–2014 decreased welfare across most of the world. In the US, Southern and Western states were made worse off, and the climate shocks induced the US population to shift eastward, and increased nonemployment. To quantify the future impacts of climate change, we shock our model a high probability climate change trajectory (SSP2-4.5 or RCP4.5) that results in global average warming of 2.5°C by 2100. This climate scenario results in welfare gains in parts of Europe and North America, but significant losses elsewhere. The global impact is a welfare loss of 10.9%, while the US has welfare gains of 1.6%. The largest gains in the US are in the Northeast while the largest losses accrue to states in the South such as Texas, Louisiana, and Missouri. In response to climate change, the US population migrates from the South and West to the Midwest and Northeast, and workers are drawn out of nonemployment and into the workforce. Climate change also causes the composition of the US economy to further shift from manufacturing to services, amplifying current structural trends. The ultimate welfare outcome during both 2000–2014 and 2015–2100 is highly sensitive to whether the model accounts for amenities, input-output loops, temperature variability, and industry-level heterogeneity in the productivity effects of temperature, indicating that aggregation in climate-economy models may not be an innocuous choice.

To quantify the value of adaptation through trade, migration, and industry switching, we focus on the expected future impact of climate and analyze counterfactuals in which we prevent them from endogenously adjusting to climate shocks. Trade, industry switching, and migration combined increase US welfare by 13.7 percentage points, turning an overall welfare loss of 12.1% without any adaptation into a gain of 1.6%. We find that trade adaptation is beneficial to all states and is by far the primary driver of the value of adaptation, accounting for over 90% of the total gains from adaptation. Adaptation through industry switching accounts for approximately a fifth of the total gains from adaptation, while adaptation through migration has the smallest effect, accounting for only 8% of the total gains from adaptation. Market-based adaptation is most valuable in Southeastern US where states such as Alabama experience an additional 20 percentage point drop in welfare if workers and trade patterns do not adjust to changes in climate, while adaptation actually makes households in Alaska worse off due to pecuniary externalities.

Our final set of results show that the value of market-based adaptation hinges upon the representation of economic and climatic heterogeneity. Heterogeneity across industries in their response to climate change creates the potential for welfare to improve from workers switching into the most productive industries. If climate impacts are forced to be homogeneous due to aggregation of industries, these potential welfare gains will be overlooked. We find that accounting for industrial heterogeneity reduces the costs of climate change in the US by 18 percentage points, and is a significant driver of the benefits obtained from adaptation through trade and industry switching.

Heterogeneity in temperature variability also has first-order effects on welfare. Representing heterogeneity in within-year temperature variability, and within-year temperature variability itself, matters because it changes exposure to extreme hot and cold temperatures, even holding the mean constant. Climate scientists predict that there will be heterogeneous changes in temperature variability across countries, even though the global average variability may not change (Huntingford et al., 2013; Holmes et al., 2016; Bathiany et al., 2018).[6] We find that the predicted changes in temperature variability through 2100 reduce US welfare by 9–12 percentage points. Unlike industrial heterogeneity, heterogeneity in temperature variability dampens the benefits of market-based adaptation. The reason for this counterintuitive result is that temperature variability is negatively correlated with average daily temperature so that cooler regions have higher variance daily temperatures. Higher variability tends to make cooler regions worse off relative to hotter regions, and thus reduces the total differences in climate impacts between them and as a result dampening the benefits of adaptation.

We contribute to a nascent literature at the intersection of climate impacts, growth, geography, and trade.[7] This literature has often focused on the agricultural sector and found that within-country and inter-country reallocation matters, particularly when accounting for subsistence requirements (Costinot et al., 2016; Baldos et al., 2019; Nath, 2020; Gouel and Laborde, 2021).[8] Recent work on the geography of climate change has put extra focus on the dynamics. Dynamics are important for correctly understanding the economic impacts of sea level rise, for constructing spatially detailed integrated assessment models, and for identifying how migration responds to changes in climate (Desmet and Rossi-Hansberg, 2015; Balboni, 2019; Conte et al., 2020; Alvarez and Rossi-Hansberg, 2021; Desmet et al., 2021). Efforts similar to ours in the macroeconomics literature have aimed to bridge the gap between micro-estimates and macro-modeling of the growth effects of natural disasters (Bakkensen and Barrage, 2018), and shown that idiosyncratic risk matters for welfare (Fried, 2021).[9]

We advance this literature in several ways. First, we consider a granular set of industries, and our dynamic-spatial framework allows us to quantify the value of several adaptation mechanisms. Second, our paper provides the first evidence of the economic value of industrial heterogeneity and temperature variability, and shows how heterogeneity itself matters for market-based adaptation. Third, we use the rich structure of our model and a small set of observable variables to empiri-

[6] The evidence points to increased variability in poorer and hotter countries, magnifying the negative effects of an upward shift in mean temperature (Bathiany et al., 2018). Figure A6 in the Appendix shows that there is significant heterogeneity across locations in the change of daily temperature variability in our data.

[7] There is also an extensive literature studying how trade affects emissions and pollution rather than how it modulates the impacts of environmental shocks (e.g. Antweiler et al., 2001; Copeland and Taylor, 2004; Shapiro, 2016; Shapiro and Walker, 2018).

[8] Others have shown that the effect of temperature on reallocation through trade can be observed in the data (Jones and Olken, 2010). Migration has also played a large role in adaptation to a variety of environmental shocks and natural disasters (Hornbeck, 2012; Boustan et al., 2012; Missirian and Schlenker, 2017; Deryugina and Hsiang, 2017).

[9] There is also a large related macro-growth literature focused on the theoretical foundations of climate policy (e.g. Acemoglu et al., 2012; Golosov et al., 2014), and an integrated assessment literature quantifying optimal climate policy (e.g. Nordhaus, 2017; Lemoine and Rudik, 2017).

cally estimate impacts of climate change while accounting for trade linkages and forward-looking households. Using these model-derived response functions in our quantitative simulations provides internal consistency between our estimation and quantification.[10]

We also contribute to the empirical climate literature by providing a framework to identify the effect of climate change on economic growth and amenities in dynamic-spatial general equilibrium. The specifications used in the literature been motivated by a variety of theoretical models, ranging from partial equilibrium to multi-country general equilibrium (Dell et al., 2012; Burke et al., 2015; Lemoine, 2018; Kahn et al., 2019).[11] Our estimating approach uses a multi-industry dynamic-spatial equilibrium foundation, and we also harness the full empirical distribution of daily temperature instead of relying on moments like annual means. Our specifications show that dynamics and spatial linkages matter for identifying the effects of climate change, and that using the full distribution of temperature is necessary because temperature variability has first-order effects.

Finally, we make a methodological contribution to trade and economic geography. Our welfare and quantitative decomposition methodology builds on those in both static (Costinot et al., 2016) and dynamic settings (Artuc et al., 2010; Caliendo et al., 2019). This literature has largely focused on responses to changes in economic fundamentals like trade costs or migration costs (Costinot, Donaldson and Komunjer, 2012; Caliendo, Opromolla, Parro and Sforza, 2017) while we provide new quantitative tools for isolating the role of market mechanisms in adapting to arbitrary shocks to economic fundamentals.[12]

2 A Dynamic-Spatial Model of Trade and Climate Change

Our theoretical framework builds on the dynamic forward-looking setting of Caliendo, Dvorkin and Parro (2019, henceforth CDP), augmented to allow for temperature effects on productivity growth and local amenities. Formally, our economy has N regions indexed by n, i, and l; and K industries indexed by k, s, and h. Each market is defined as a region-industry. Each industry is composed of a continuum of goods or varieties $\xi \in \Xi \equiv [0, 1]$, and goods markets are all competitive.

In every market, each firm has access to a constant returns to scale production technology that uses labor, local structures, and intermediate inputs, and produces a different good or variety ξ. As in Eaton and Kortum (2002, henceforth EK), productivity for good ξ in any market is independently drawn from a Fréchet distribution with an industry-specific productivity dispersion parameter θ^k.

[10] Although our paper includes substantial detail on reallocation and impacts on growth and amenities, it does not account for capital destruction, mortality costs, or firm-side adaptive capital investments which previous work has shown plays a significant role in the costs of climate change (Dietz and Stern, 2015; Bakkensen and Barrage, 2018; Carleton et al., 2020).

[11] Colacito et al. (2018) estimate the effect of temperature on growth in the United States and explore heterogeneity across sectors and states without microfounding their approach. Newell et al. (2021) take a machine learning approach to understand out-of-sample predictive power of different specifications. Deryugina and Hsiang (2017) estimate the effect of temperature on the level of income in a static general equilibrium model.

[12] See Costinot and Rodríguez-Clare (2014); Kucheryavyy, Lyn and Rodríguez-Clare (2020) for a discussion of welfare decomposition across an important class of static trade models.

Time is discrete and denoted by t. In our model each time period t represents one year. In a similar spirit to Artuc, Chaudhuri and McLaren (2010), households are forward-looking, and optimally decide the market to work and live in every time period given the current distribution of labor across markets and amenities across regions. Households make migration decisions based on bilateral costs of moving across markets, as well as the idiosyncratic shock they receive in each market. Once migration decisions are made, the labor market clears and households receive the marginal product of their labor. Preferences are defined by a flow utility function over consumption and amenities. Each household maximizes the expected present value of the sum of future flow utilities.

We now formally describe each segment of our economy, beginning with households and then firms.

2.1 Consumption and Labor Supply

In our model households make two types of decisions: consumption choices and forward-looking migration decisions. We begin with their consumption choices. At every time period, households in each region either supply their one unit of labor inelastically to a specific industry, or are nonemployed and engage in home production ($k = 0$). Households who are employed receive a competitive, industry-specific market wage $w^k_{n,t}$ equivalent to the value of their marginal product of labor, while nonemployed households in home production receive a level of consumption $C^0_{n,t} = b^n > 0$ that is region-specific and time-invariant. Employed households in each region optimally allocate income according to preferences:

$$U(C^k_{n,t}, B_{n,t}) = \log\left(B_{n,t} C^k_{n,t}\right)$$

where $B_{n,t}$ defines the local amenities in region n at time t. We assume that $B_{n,t}$ is multiplicatively separable in a vector of daily temperature variables $\mathbf{T_{n,t}}$:

$$B_{n,t} = \bar{B}_{n,t} \exp\left(f(\mathbf{T_{n,t}}; \zeta_{\mathbf{B}})\right) \tag{1}$$

where $\bar{B}_{n,t}$ captures exogenous non-temperature amenities, $\exp\left(f(\mathbf{T_{n,t}}; \zeta_{\mathbf{B}})\right)$ is the temperature component of amenities, f is an arbitrary function of $\mathbf{T_{n,t}}$, and $\zeta_{\mathbf{B}}$ is a set of parameters to be estimated that govern how daily temperature affects local amenities.

Households in market (n, k) at time t choose to consume goods from each industry s, $c^{ks}_{n,t}$, which aggregates to an overall basket of goods from different industries given by:

$$C^k_{n,t} = \prod_{s=1}^{K} \left(c^{ks}_{n,t}\right)^{\alpha^s}, \tag{2}$$

where $\alpha^s \in (0, 1)$ for all s is the consumption share of goods from each industry with $\sum_{s=1}^{K} \alpha^s = 1$. Each industry bundle $c^{ks}_{n,t}$ is a constant-elasticity-of-substitution (CES) aggregate of all varieties with elasticity $\sigma^s > 0$. The ideal price index is then given by the standard Cobb-Douglas aggregator:

$$P_{n,t} = \prod_{s=1}^{K} \left(P_{n,t}^s / \alpha^s\right)^{\alpha^k} \tag{3}$$

where $P_{n,t}^s$ is the price index of goods purchased from industry s for final consumption in location n, as defined later on. Note that all households in region n, regardless of the industry they work in, face the same price index.

We now present the intertemporal migration decisions of the households. In the initial time period there is a mass of $L_{n,0}^k$ households in each region n and industry k. Households are forward-looking and discount the future at a common rate $\beta \in (0,1)$. In each time period t, households residing in region n and working in industry k supply their one unit of labor inelastically, receive wages or home production, and make consumption decisions, as described above. Households then observe the conditions of the economy and climate in all labor markets, and the realization of their own idiosyncratic shock $\epsilon_{i,t}^s$. At the end of each time period, households choose whether to relocate to another market (i,s) in the same country, with migration costs μ_{ni}^{ks} that are time-invariant, specific to each origin-destination pair of markets, and measured in terms of utility.[13]

Households will choose to move to the market with the highest present value stream of utility minus any migration costs. The optimization problem for a household in market (n,k) at time t is:

$$v_{n,t}^k = \max_{\{i,s\}_{i=1,s=0}^{N,K}} U\left(C_{n,t}^k, B_{n,t}\right) + \left\{\beta \mathbb{E}_t\left(\mathbb{E}_\epsilon\left[v_{i,t+1}^s\right]\right) - \mu_{ni}^{ks} + \nu \epsilon_{i,t}^s\right\} \tag{4}$$

$$C_{n,t}^k \equiv \begin{cases} b_n & \text{for } k = 0, \\ w_{n,t}^k / P_{n,t} & \text{otherwise;} \end{cases}$$

where $\mathbb{E}_t(\cdot)$ is the time-t expectation over future state variables which could capture technology shocks, policy shocks which could affect output, climate shocks, and the like. $\mathbb{E}_\epsilon(\cdot)$ is the expectation over the household's future realizations of the idiosyncratic shock. ν is a scalar that captures the migration elasticity of households across markets.

As is common in the discrete choice literature, we assume the idiosyncratic shock $\epsilon_{i,t}^s$ is an independently and identically distributed Type-I Extreme Value random variable with zero mean. This assumption allows us to aggregate the decision-making of individual households in closed-form.

[13]For the purposes of our empirical and quantitative application, we only observe migration flows in the US and thus cannot identify μ_{ni}^{ks} in other countries. As a result we assume that there is no migration across countries. We further assume that $\mu_{ni}^{ks} = 0$ for all $n = i$ outside the US so that there is free mobility to switch into different industries, and since the non-US countries have no sub-country representation, there is no within-country migration across regions.

Letting $V_{n,t}^{k} \equiv \mathbb{E}_{\epsilon}\left[v_{n,t}^{k}\right]$ and taking an expectation with respect to ϵ over equation (4) yields:

$$\begin{aligned} V_{n,t}^{k} = U\left(C_{n,t}^{k}, B_{n,t}\right) + \nu \log\left(\sum_{i=1}^{N}\sum_{s=0}^{K} \exp\left[\left(\beta \mathbb{E}_{t}\left(V_{i,t+1}^{s}\right) - \mu_{ni}^{ks}\right)/\nu\right]\right) \\ + \nu \log\left(\sum_{i=1}^{N}\sum_{s=0}^{K} \exp\left[\left(\beta \mathbb{E}_{t}\left(V_{i,t+1}^{s}\right) - \mu_{ni}^{ks}\right)/\nu\right]\right). \end{aligned} \tag{5}$$

The Type-I Extreme Value assumption on the idiosyncratic shocks also delivers an analytical expression for migration shares. Defining $\pi_{ni,t}^{ks}$ as the share of households that move from region n and industry k to region i and industry s, we obtain:

$$\pi_{ni,t}^{ks} = \frac{\exp\left[\left(\beta \mathbb{E}_{t}\left(V_{i,t+1}^{s}\right) - \mu_{ni}^{ks}\right)/\nu\right]}{\sum_{l=1}^{N}\sum_{h=0}^{K} \exp\left[\left(\beta \mathbb{E}_{t}\left(V_{l,t+1}^{h}\right) - \mu_{nl}^{kh}\right)/\nu\right]}. \tag{6}$$

Equation (6) shows that, all else constant, there will be greater in-migration to markets with higher lifetime net utilities.

Given the migration shares, the evolution of the labor distribution across markets over time $\left\{L_{n,t}^{k}\right\}_{n=1,k=0}^{N,K}$ is captured by the following equation for each time t:

$$L_{n,t+1}^{k} = \sum_{i=0}^{N}\sum_{s=0}^{K} \pi_{in,t}^{sk} L_{i,t}^{s}. \tag{7}$$

Since households choose where to relocate to at the end of each period, labor supply at the beginning of any period t is already determined by previous actions. With this timing, we now proceed to describe the static production structure which, conditional on the labor supplied in every market at each time t, allows us to derive equilibrium wages that clear the labor market.

2.2 Production And Labor Demand

Producers in region n and industry k at time t adopt a two-tier Cobb-Douglas constant returns to scale technology:

$$q_{n,t}^{k} = z_{n}^{k}\left[(H_{n}^{k})^{\psi^{k}}(L_{n,t}^{k})^{1-\psi^{k}}\right]^{\gamma_{n}^{k}} \prod_{s=1}^{K}\left(M_{n,t}^{ks}\right)^{\gamma_{n}^{ks}}, \tag{8}$$

where H_{n}^{k} are local structures, $L_{n,t}^{k}$ are labor inputs, and $M_{n,t}^{ks}$ are intermediate inputs produced in industry s in the same region. ψ^{k} represents the share of local structures in value added, γ_{n}^{k} represents the share of value added, and γ_{n}^{ks} represents the share of intermediate inputs produced in sector s in the same region, with $\gamma_{n}^{k} + \sum_{s=1}^{K}\gamma_{n}^{ks} = 1$. The unit price of an input bundle is given by:

$$x_{n,t}^{k} = \kappa_{n}^{k}\left(\left(r_{n,t}^{k}\right)^{\psi^{k}}\left(w_{n,t}^{k}\right)^{1-\psi^{k}}\right)^{\gamma_{n}^{k}} \prod_{s=1}^{K}\left(P_{n,t}^{s}\right)^{\gamma_{n}^{ks}}, \tag{9}$$

where κ_n^k is a constant, $r_{n,t}^k$ is the rental rate of local structures, and $P_{n,t}^k$ also represents the price of the local industry aggregate of varieties used as intermediate inputs in production.[14]

A producer of variety ξ in market (n,k) produces $q_{n,t}^k(\xi)$ units of output, given exogenous productivity $z_n^k(\xi)$. As in EK, we assume that for all regions n, industries k, and their varieties ξ, $z_n^k(\xi)$ is a random variable drawn independently for each triplet (n,k,ξ) from a Fréchet distribution $F_{n,t}^k(\cdot)$ such that:

$$F_{n,t}^k(z) = \exp\left[-Z_{n,t}^k(z)^{-\theta^k}\right]. \tag{10}$$

The shape parameter θ^k measures the strength of intra-industry heterogeneity and captures the extent to which there are idiosyncratic differences in technological know-how across varieties. The scale parameter $Z_{n,t}^k > 0$ represents the time-varying fundamental productivity of market (n,k), and embodies factors such as climate, infrastructure and institutions that affect the productivity of all producers at time t in a given region and industry. We assume that the fundamental productivity of region n in industry k grows at some time-varying base rate $\wp_{n,t}^k$ but adjusted for temperature effects:

$$\frac{Z_{n,t}^k}{Z_{n,t-1}^k} = (1+\wp_{n,t}^k)\exp\left(g(\mathbf{T}_{n,t};\zeta_{\mathbf{Z}}^k)\right). \tag{11}$$

$\mathbf{T}_{n,t}$ is a vector of daily temperature variables in region n in year t, as explained in the household problem. $g(\mathbf{T}_{n,t};\zeta_{\mathbf{Z}}^k)$ is a flexible temperature response function. We assume that g is linear in the parameter vector $\zeta_{\mathbf{Z}}^k$, which we will estimate.

2.3 Trade and Market Clearing

Trade costs are of the standard iceberg type, so that delivering one unit of any good in industry k from region i to region n at time t requires shipping $\tau_{ni,t}^k \geq 1$ units of the good, with $\tau_{nn,t}^k = 1$ for all n and k, and $\tau_{ni,t}^k \leq \tau_{nl,t}^k \tau_{li,t}^k$ for all i, n, l and k (triangular inequality). The price of each variety ξ in industry k and region n is the minimum unit cost across regions:

$$p_{n,t}^k(\xi) = \min_{1\leq i\leq N}\left\{\frac{\tau_{ni,t}^k x_{i,t}^k}{z_{i,t}^k(\xi)}\right\}.$$

Let $X_{ni,t}^k$ denote the time t total expenditure of region n on goods from region i in industry k, $X_{n,t}^k \equiv \sum_{l=1}^N X_{nl,t}^k$ denote the total expenditures of region n in industry k, and $\lambda_{ni,t}^k \equiv X_{ni,t}^k / X_{n,t}^k$ denote industry-level bilateral trade shares. Following the procedure in EK yields:

$$\lambda_{ni,t}^k = \frac{Z_{i,t}^k\left(x_{i,t}^k \tau_{ni,t}^k\right)^{-\theta^k}}{\sum_l Z_{l,t}^k\left(x_{l,t}^k \tau_{nl,t}^k\right)^{-\theta^k}}. \tag{12}$$

[14] The latter is the typical assumption that both consumers and producers of intermediate inputs use the same CES aggregator over industry varieties.

In turn, the price index for industry k in region n is:

$$P_{n,t}^k = \Gamma^k \left(\sum_{l=1}^{N} Z_{l,t}^k \left(x_{l,t}^k \tau_{nl,t}^k \right)^{-\theta^k} \right)^{-1/\theta^k}, \tag{13}$$

where Γ^k is a constant, and $1+\theta^k > \sigma^k$.[15] The latter is the usual technical assumption guaranteeing a well-defined price index.

Finally, our model also allows for trade imbalances. In each location n, there is a mass 1 of local capitalists. They own local structures, rent them to local producers, and invest their rents in a global portfolio. They in turn receive a constant share ι_n from the global portfolio, with $\sum_{n=1}^{N} \iota_n = 1$. Capitalists spend this income across local goods from different industries like households, given by equation (2). Trade imbalances are thus given by the difference between the rents capitalists collect and the income they receive from the global portfolio, i.e. $\sum_{k=1}^{K} r_{n,t}^k H_n^k - \iota_n \chi_t$, where $\chi_t = \sum_{i=1}^{N} \sum_{k=1}^{K} r_{n,t}^k H_n^k$ are the total revenues in the global portfolio at time t. Note that trade imbalances vary over time due to changes in rental prices for local structures.

In each market (n,k), goods market clearing implies that total expenditures is equal to total income:

$$X_{n,t}^k = \sum_{s=1}^{K} \gamma_n^{ks} \sum_{i=1}^{N} \lambda_{ni,t}^k X_{i,t}^k + \alpha^k \sum_{k=1}^{K} w_{n,t}^k L_{n,t}^k + \alpha^k \iota_n \chi_t. \tag{14}$$

Total income has three components. The first term on the right-hand side is the total expenditure of firms in all markets on goods produced in market (n,k), the second term is the total income of households residing and working in market (n,k), and the third term is the total income of local capitalists in market (n,k). Additionally, labor market clearing in market (n,k) is given by:

$$w_{n,t}^k L_{n,t}^k = \gamma_n^k (1-\psi^k) \sum_{i=1}^{N} \lambda_{in,t}^k X_{i,t}^k \tag{15}$$

and market clearing for local structures is:

$$r_{n,t}^k H_n^k = \gamma_n^k \psi^k \sum_{i=1}^{N} \lambda_{in,t}^k X_{i,t}^k. \tag{16}$$

2.4 Equilibrium

Given the distribution of labor across markets $L_t \equiv \left\{ L_{n,t}^k \right\}_{n=1,k=0}^{N,K}$, local structures $H \equiv \{H_n^k\}_{n=1,k=0}^{N,K}$, location-industry fundamental productivities $Z_t \equiv \left\{ Z_{n,t}^k \right\}_{n=1,k=1}^{N,K}$, industry-level bilateral trade costs $\tau_t \equiv \left\{ \tau_{ni,t}^k \right\}_{n=1,i=1,k=0}^{N,N,K}$, migration costs $\mu \equiv \left\{ \mu_{ni}^{ks} \right\}_{n=1,i=1,k=0,s=0}^{N,N,K,K}$ and home production $b = \{b_n\}_{n=1}^{N}$, we define a time-t **momentary equilibrium** as a vector of wages $w_t \equiv \left\{ w_{n,t}^k \right\}_{n=1,k=1}^{N,K}$ sat-

[15] Specifically, $\Gamma^k \equiv \Gamma \left(\frac{1-\sigma^k+\theta^k}{\theta^k} \right)^{\frac{1}{1-\sigma^k}}$, where Γ is the Gamma function.

isfying equilibrium conditions (9) and (12) – (16) of the static sub-problem. This equilibrium is the solution to a static multi-regional and multi-industry trade model. Let $\pi_t \equiv \left\{\pi_{ni,t}^{ks}\right\}_{n=1,i=1,k=0,s=0}^{N,N,K,K}$, $B_t \equiv \{B_{n,t}\}_{n=1}^{N}$ and $V_t \equiv \left\{V_{n,t}^{k}\right\}_{n=1,k=0}^{N,K}$ be migration shares, amenities, and lifetime utilities respectively. Given an initial allocation of labor L_0, time-invariant exogenous fundamentals μ, b and H, and a path of time-varying exogenous fundamentals $\{B_t, Z_t, \tau_t\}_{t=0}^{\infty}$, we define a **sequential competitive equilibrium** as a sequence of $\{L_t, \pi_t, V_t, w_t\}_{t=0}^{\infty}$ that solves equilibrium conditions (5) – (7) and the temporary equilibrium at each time t. Finally, we define a **stationary equilibrium** as a sequential competitive equilibrium such that the sequence $\{L_t, \pi_t, V_t, w_t\}_{t=0}^{\infty}$ is constant for every t.

3 Estimating the Effects of Climate Change in Dynamic-Spatial Equilibrium

In this section we describe how we estimate the effects of climate change on productivity growth and amenities. Both estimation approaches are derived from the dynamic-spatial equilibrium conditions of the model and thus capture the direct impact of climate change on the objects of interest without any confounding from spatial spillovers or forward-looking behavior that are represented by the model.

Before introducing our estimating equations we first describe how we construct the temperature response functions for productivity growth and amenities, $g(\mathbf{T}_{n,t}; \zeta_{\mathbf{Z}}^{k})$ and $f(\mathbf{T}_{n,t}; \zeta_{\mathbf{B}})$. Our primary goal for the construction of the response functions is to allow for non-linear impacts from daily temperature extremes and changes in the within-year variation in temperature. We begin with the distribution of daily average temperature in each region-year from the historical temperature record and climate model simulations. We then discretize the distribution into bins of 1°C where the values across all 1°C bins sum up to the number of days in a year, and the total annual effect is the sum of the individual daily effects. We Windsorize the distribution so there is a lower bin containing all daily temperatures ≤-15°C and an upper bin containing daily temperatures ≥50°C. Similar to Schlenker and Roberts (2009), we evaluate each daily temperature using a second-degree orthogonal polynomial, and sum up the first and second-degree terms across all days of the year.[16] The $\zeta_{\mathbf{Z}}^{k}$ and $\zeta_{\mathbf{B}}$ terms in g and f correspond to the coefficients on the polynomial sums. The levels of g and f at each temperature thus tell us the effect of an additional day of the year at that temperature on annual production growth and local amenities. Figure A5 in the Appendix shows the estimated response functions using orthogonal polynomial approximations up to degree six, and spline approximations up to five evenly spaced knots.

[16] An alternative way to describe this is we are using a second-degree approximation to force a particular relationship between our temperature bins rather than estimating 66 separate coefficients.

3.1 Effects on Productivity Growth

To estimate the direct effect of temperature on productivity growth, we use the equilibrium conditions of the model governing bilateral trade flows. Recall that from equations (12) and (13) we can write the expenditures of region n on industry k goods from region i as:

$$X^k_{ni,t} = \left(\Gamma^k\right)^{-\theta^k} \frac{Z^k_{i,t}\left(x^k_{i,t}\right)^{-\theta^k}\left(\tau^k_{ni,t}\right)^{-\theta^k}}{\left(P^k_{n,t}\right)^{-\theta^k}} X^k_{n,t}.$$

Normalizing the above equation by the importer's own expenditures X^k_{nn} in industry k gives:

$$\frac{X^k_{ni,t}}{X^k_{nn,t}} = \frac{Z^k_{i,t}\left(x^k_{i,t}\right)^{-\theta^k}\left(\tau^k_{ni,t}\right)^{-\theta^k}}{Z^k_{n,t}\left(x^k_{n,t}\right)^{-\theta^k}}.$$

Dividing by its lag, using equation (11) to substitute in for the Z^k terms, and taking the logarithm on both sides and rearranging we obtain:

$$\begin{aligned} \log\left(\frac{X^k_{ni,t}/X^k_{nn,t}}{X^k_{ni,t-1}/X^k_{nn,t-1}}\right) &= \left[g(\mathbf{T}_{i,t};\zeta^k_{\mathbf{Z}}) - g(\mathbf{T}_{n,t};\zeta^k_{\mathbf{Z}})\right] + \log\left(\frac{1+\wp^k_{i,t}}{1+\wp^k_{n,t}}\right) \\ &\quad - \theta^k \log\left(\frac{\tau^k_{ni,t}}{\tau^k_{ni,t-1}}\right) - \theta^k \log\left(\frac{x^k_{i,t}}{x^k_{i,t-1}} \Big/ \frac{x^k_{n,t}}{x^k_{n,t-1}}\right). \end{aligned}$$

Since $g(\mathbf{T}_{n,t};\zeta^k_{\mathbf{Z}})$ is linear in $\zeta^k_{\mathbf{Z}}$, this gives us an equation that is linear in parameters. The growth of bilateral trade expenditures normalized by own-expenditures is a function of four terms. The first term is the difference in the two countries' productivity growth responses to local temperature. The second is the difference in the unobserved fundamental productivity base growth rates. The third term is the growth in bilateral trade costs. The fourth term is the difference in growth of input costs. Input costs are not directly observed in the data, but in the appendix we show how we can estimate them using equation (9) and another equilibrium condition of the model that yields the price indices.

The unit of observation for this equation is an importer-exporter-industry-year. We use the following as our main specification for estimating the response function:

$$\begin{aligned} \log\left(\frac{X^k_{ni,t}/X^k_{nn,t}}{X^k_{ni,t-1}/X^k_{nn,t-1}}\right) &= \left[g(\mathbf{T}_{i,t} - \mathbf{T}_{n,t};\zeta^k_{\mathbf{Z}})\right] - \theta^k \log\left(\frac{\tau^k_{ni,t}}{\tau^k_{ni,t-1}}\right) \\ &\quad - \theta^k \log\left(\frac{x^k_{i,t}}{x^k_{i,t-1}} \Big/ \frac{x^k_{n,t}}{x^k_{n,t-1}}\right) + \rho^k_t + \varphi^k_{ni} + \varepsilon^k_{ni,t} \end{aligned} \tag{17}$$

where $g(\mathbf{T}_{i,t};\zeta^k_{\mathbf{Z}}) - g(\mathbf{T}_{n,t};\zeta^k_{\mathbf{Z}}) = g(\mathbf{T}_{i,t} - \mathbf{T}_{n,t};\zeta^k_{\mathbf{Z}})$ and the ζ^k_Z terms are the coefficients we will estimate. Our empirical specification also includes importer-exporter-industry fixed effects φ^k_{ni} and industry-year fixed effects ρ_t^k to control for components of the unobserved fundamental growth rates that may be correlated with temperature. The error term $\varepsilon_{ni,t}^k$ thus captures within-industry components of fundamental base productivity growth that are changing differentially within an importer-exporter-industry triplet over time. The vector of ζ_Z^k's is well-identified if these components are not correlated with temperature. We cluster our standard errors two ways at the importer and exporter level to account for autocorrelation and within-country correlation in errors across trading partners or industries. In our empirical application we estimate both the average response function across all industries, $\zeta_{\mathbf{Z}}$, as well as industry-specific response functions, $\zeta_{\mathbf{Z}}^k$. The industry-specific response functions come from a single regression where we interact the response function g with a set of industry dummy variables.

3.2 Effects on Local Amenities

To estimate the effect of temperature on amenities, we exploit variation in migration flows, wages, and distributions of daily temperature. We begin with the expected lifetime utility of a household in region n and sector k in equation (5), which may alternatively be expressed as:

$$V_{n,t}^k = \underbrace{U\left(C_{n,t}^k, B_{n,t}\right)}_{\text{instantaneous utility}} + \underbrace{\beta \mathbb{E}_t(V_{n,t+1}^k)}_{\text{base value staying in market}} + \underbrace{\mathbb{E}_\epsilon\left[\max_{\{i,s\}_{i=1,s=0}^{N,K}} \left\{\nu \epsilon_{i,t}^s + \nu \bar{\epsilon}_{ni,t}^{ks}\right\}\right]}_{\text{option value of moving markets}} \tag{18}$$

where $V_{n,t}^k \equiv \mathbb{E}_\epsilon\left[v_{n,t}^k\right]$ and:

$$\bar{\epsilon}_{ni,t}^{ks} \equiv \frac{1}{\nu}\left[\beta \mathbb{E}_t\left(V_{i,t+1}^s - V_{n,t+1}^k\right) - \mu_{ni}^{ks}\right] \tag{19}$$

represents the difference in idiosyncratic benefits $(\epsilon_{n,t}^k - \epsilon_{i,t}^s)$ at which a worker in market (n,k) is indifferent between staying in the same market and moving to market (i,s). We show in Appendix B.2 that the expected utility of a household in each market can be converted into an Euler equation:

$$\nu \bar{\epsilon}_{ni,t}^{ks} + \mu_{ni}^{ks} = \beta \mathbb{E}_t\left[U(C_{i,t+1}^s, B_{i,t+1}) - U(C_{n,t+1}^k, B_{n,t+1}) + \nu \bar{\epsilon}_{ni,t+1}^{ks} + \mu_{ni}^{ks} + \Omega(\bar{\epsilon}_{i,t+1}^s) - \Omega(\bar{\epsilon}_{n,t+1}^k)\right]$$

where:

$$\Omega(\bar{\varepsilon}_{\mathbf{t}}^{\mathbf{nk}}) \equiv \mathbb{E}_\epsilon\left[\max_{\{i,s\}_{i=1,s=0}^{N,K}} \left\{\nu \epsilon_{i,t}^s + \nu \bar{\epsilon}_t^{nk,is}\right\}\right].$$

We then convert the Euler equation to the following moment condition (Artuc et al., 2010):

$$\mathbb{E}_t\left[\frac{\beta}{\nu}\log\left(\frac{B_{i,t+1}}{B_{n,t+1}}\frac{C_{i,t+1}^s}{C_{n,t+1}^k}\right) + \beta \log\left(\frac{\pi_{ni,t+1}^{ks}}{\pi_{ii,t+1}^{ss}}\right) - \log\left(\frac{\pi_{ni,t}^{ks}}{\pi_{nn,t}^{kk}}\right) + \frac{\beta - 1}{\nu}\mu_{ni}^{ks}\right] = 0. \tag{20}$$

Rearranging the moment condition, using equation (1), and substituting changes in consumption with changes in real wages, we can derive a linear equation:

$$\log\left(\frac{\pi_{ni,t}^{ks}}{\pi_{nn,t}^{kk}}\right) = \frac{\beta}{\nu}\left[f(\mathbf{T_{i,t+1}};\zeta_{\mathbf{B}}) - f(\mathbf{T_{n,t+1}};\zeta_{\mathbf{B}})\right] + \frac{\beta}{\nu}\log\left(\frac{\bar{B}_{i,t+1}}{\bar{B}_{n,t+1}}\right)$$
$$+\frac{\beta-1}{\nu}\mu_{ni}^{ks} + \beta\log\left(\frac{\pi_{ni,t+1}^{ks}}{\pi_{ii,t+1}^{ss}}\right) + \frac{\beta}{\nu}\log\left(\frac{\omega_{i,t+1}^{s}}{\omega_{n,t+1}^{k}}\right) + \varepsilon_{ni,t}^{ks}.$$

The current ratio of the migration share to market (i, s) relative to the share of those who remain in (n, k) has four components. The first is the one period ahead differences in amenities which is captured by the terms on the first line. This consists of differences in temperature impacts on amenities $f(\mathbf{T}_{i,t+1};\zeta_B) - f(\mathbf{T}_{n,t+1};\zeta_B)$, and differences in unobserved non-temperature related amenities $\frac{\overline{B}_{i,t+1}}{\overline{B}_{n,t+1}}$. The second component is the first term on the second line, the unobserved moving costs. The third component is the one period ahead migration share ratio which captures differences in option value in market (n, k) relative to market (i, s), and acts as a sufficient statistic for future welfare beyond time period $t + 1$. Conditioning on this term is what allows us to isolate the effect of climate change on flow utility in a model with forward-looking behavior. The last component is the one period ahead difference in wages which captures relative differences in flow payoffs next period. We calibrate β to an annual rate of 0.96 and $\nu = 2.02$ following CDP in order to focus on the estimation of ζ_B, the set of amenity-temperature response parameters.

After pinning down β and ν, our specification for estimating the effect of temperature on amenities is:

$$\begin{aligned} &\log\left(\frac{\pi_{ni,t}^{ks}}{\pi_{nn,t}^{kk}}\right) - \beta\log\left(\frac{\pi_{ni,t+1}^{ks}}{\pi_{ii,t+1}^{ss}}\right) - \frac{\beta}{\nu}\log\left(\frac{\omega_{i,t+1}^{s}}{\omega_{n,t+1}^{k}}\right) \\ = \quad &\frac{\beta}{\nu}\left[f(\mathbf{T_{i,t+1}} - \mathbf{T_{n,t+1}};\zeta_{\mathbf{B}})\right] + \delta_t^k + \varphi_{ni}^k + \varepsilon_{ni,t}^{ks} \end{aligned} \tag{21}$$

where we set $s = k$ since $\zeta_{\mathbf{B}}$ is only identified off migration variation. φ_{ni}^k is an origin-destination-industry effect and δ_t^k is an industry-year effect. These fixed effects are included to full capture the unobserved real world migration costs μ_{ni}^{ks}, and components of local amenities $\frac{\bar{B}_{i,t+1}}{\bar{B}_{n,t+1}}$. $f(\mathbf{T_{i,t+1}};\zeta_{\mathbf{B}})$ is generated in the same way as $g(\mathbf{T_{i,t+1}};\zeta_{\mathbf{Z}})$ was for productivity effects using the binned daily temperatures and second-order orthogonal polynomials. We cluster our standard errors two ways at the origin and destination to account for correlation in shocks across origins for each destination, and across destinations for each origin.

3.3 Data for Estimation of Response Functions

We use data on bilateral trade expenditures from the World Input Output Database (WIOD) (Timmer et al., 2015). The WIOD reports bilateral trade flows for 43 countries and an aggregate for the rest of the world from 2000–2014. Data are reported for 56 different industries, but we aggregate these up to 20 industries to better match the data available for the counterfactual simulations.

We integrate our economic data with temperature and precipitation data from Princeton's

Global Meteorological Forcing Dataset (GMFD) for land surface modeling.[17] The GMFD provides gridded daily data on temperature and precipitation over 1948-2016 with a 0.25 degree spatial resolution (around 28 km at the equator). We spatially aggregate the gridded data to each country based on population weights from 2010 (Center for International Earth Science Information Network, 2018).

Data on time-varying non-tariff trade costs come from the CEPII Gravity Dataset. Data on tariff rates come from the World Integrated Trade Solution (WITS) database. WITS reports tariffs at the 4 digit NAICS level which we aggregate up to our 20 industries using a weighted average with the weights given by the import share of each 4 digit NAICS code.

The way we construct the input costs $x_{i,t}^k$ and the necessary data for the counterfactual simulations are described in the appendix.

3.4 Temperature Response Function Estimates

The left side of Figure 1 shows the average productivity growth response function across all industries from equation (17). In the aggregate, productivity growth has an inverted-U shaped relationship with daily temperature with a peak at 14°C.[18] If a single day of the year at 14°C is replaced by a day at either -6°C or 34°C, productivity growth declines by 0.2 percentage points. Alternatively, if two days of the year at 14°C are replaced by a day at -6°C and another at 34°C, preserving the annual mean temperature, productivity growth declines by 0.4 percentage points. Changes in the higher moments of the within-year temperature distribution will have economically significant effects on productivity growth, potentially even larger than shifts in the mean. The average productivity growth response function in Figure 1 masks significant cross-industry heterogeneity. Figure A2 in the appendix shows the set of industry-specific response functions and our quantitative results show that industrial heterogeneity plays a key role in outcomes.

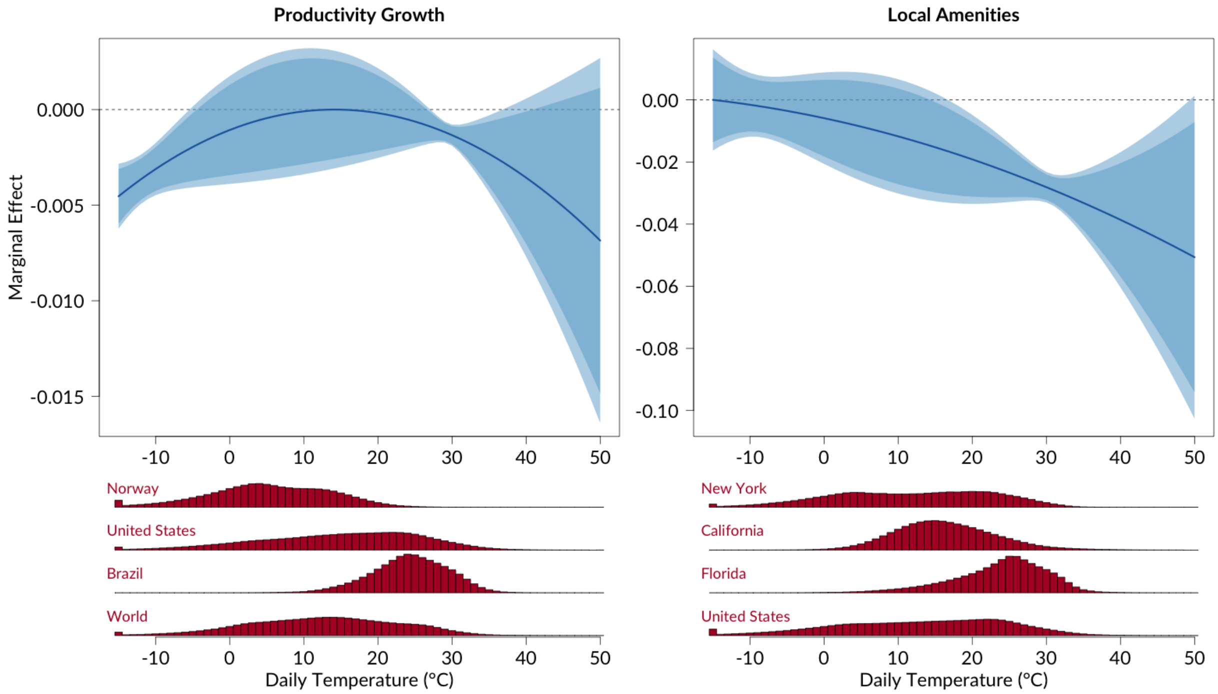
The right side of Figure 1 shows the amenity response function estimated from equation (21). The amenity response function is decreasing and concave. Replacing one day at 14°C with one at 34°C reduces welfare by 1.5%, while replacing two days at 14°C with one at -6°C and another at 34°C reduces welfare by 0.5%. Since increased variability directly reduces flow utility, households will prefer to move to locations with less extreme daily temperatures.

The histograms under the response functions show the daily temperature distribution for a select set of regions from 2000–2014. The histograms on the left show a selection of countries. Northern latitude countries tend to have most of the mass of their temperature distribution below the average productivity response function peak, while countries in the tropics have most of their mass tightly clustered above the peak. The histograms on the right show a selection of regions in the US. Northern states tend to be higher variance locations, while the Southern states tend to be lower variance. The histograms indicate that regions with higher daily average temperature have

[17] `https://hydrology.princeton.edu/data.pgf.php`

[18] Figure A5 in the Appendix shows that the shape of the growth and amenities response functions is generally robust to choices of higher order polynomials, or using cubic splines.

Figure 1: The effect of daily temperature on productivity growth and amenities.



The response functions are constructed using a second degree orthogonal polynomial approximation to the distribution of within-year daily temperatures. The temperature distributions are Windsorized at -15°C and 50°C. The shaded areas denote the 90% and 95% confidence intervals.
Left: The response function is from estimating equation (17) and reflects the average effect across all industries. Standard errors are clustered two ways at the exporter country and importer country. Figure A2 shows effects separately by industry.
Right: The response function is from estimating equation (21). Standard errors are clustered two ways at the origin state and destination state.
Bottom: The histograms show the distribution of daily average temperature for a set of locations from 2000–2014.

lower daily temperature variability.

4 Simulating and Decomposing the Impacts of Climate Change

In this section we describe how we simulate our model and implement our quantitative decomposition. First, we show how and why we express our baseline model in terms of changes over time, and then relative to a counterfactual economy also expressed in changes over time. Second, we simulate the full model with the observed annual distributions of daily temperature in the past (2000–2014), and projected distributions in the future (2015–2100), to obtain the aggregate impacts of climate change. Third, we provide an analytical decomposition of welfare to conceptualize the role of different adaptation margins. Fourth, we show how to simulate our model with different combinations of adaptation channels fixed to quantify their value and distributional effects. Finally, we show how to simulate our model when shutting down industry heterogeneity, and heterogeneity in temperature variability to identify their role on welfare and the value of adaptation.

4.1 Expressing the Model in Time and Relative Changes

Our first step is to use the dynamic hat algebra methodology to express our model in terms of changes. This transformation allows us to simulate the baseline economy and solve for counterfactual changes in the economy without knowing the levels of the time-invariant exogenous fundamentals $\bar{\Theta} = \{b, \mu, H\}$ and time-varying exogenous fundamentals $\Theta_t = \{B_t, Z_t, \tau_t\}$.[19] In what follows, we denote $\dot{Y}_{t+1} \equiv \frac{Y_{t+1}}{Y_t}$ to represent proportional time changes between time periods t and $t+1$ in the baseline model associated with the baseline fundamentals in time changes $\dot{\Theta}_t$, $\dot{Y}'_{t+1} \equiv \frac{Y'_{t+1}}{Y'_t}$ to be proportional time changes in the counterfactual model associated with the counterfactual fundamentals in time changes $\dot{\Theta}'_t$, and $\widehat{Y}_t \equiv \frac{\dot{Y}'_t}{\dot{Y}_t}$ as the counterfactual time changes $\dot{Y}'_t$ relative to the baseline time changes $\dot{Y}_t$ for any variable Y. We call $\dot{Y}_t$ changes or time changes; $\dot{Y}'_t$ counterfactual time changes; and $\widehat{Y}_t$ relative changes, relative time changes, or hat variables.

We first express the production side of our economy in time changes with the following proposition from CDP:

Proposition 1 (CDP)**.** *Given the allocation of the momentary equilibrium at t, $\{L_t, \lambda_t, X_t\}$, the solution to the momentary equilibrium at $t+1$ for a given change in $\dot{L}_{t+1}$ and $\dot{\Theta}_{t+1}$ does not require information on the level of fundamentals at t, Θ_t, or $\bar{\Theta}$. In particular, it is obtained as the solution to the following system of nonlinear equations:*

$$\dot{x}^k_{n,t+1} = \left(\dot{L}^k_{n,t+1}\right)^{\gamma^k_n \psi_n} \left(\dot{w}^k_{n,t+1}\right)^{\gamma^k_n} \prod_{s=1}^{K} \left(\dot{P}^k_{n,t+1}\right)^{\gamma^{ks}_n} \tag{22}$$

$$\dot{P}^k_{n,t+1} = \left[\sum_{i=1}^{N} \lambda^k_{ni,t} \dot{Z}^k_{i,t+1} \left(\dot{x}^k_{i,t+1} \dot{\tau}^k_{ni,t+1}\right)^{-\theta^k}\right]^{\frac{1}{\theta^k}} \tag{23}$$

$$\dot{\lambda}^k_{ni,t+1} = \left(\frac{\dot{x}^k_{n,t+1} \dot{\tau}^k_{ni,t+1}}{\dot{P}^k_{n,t+1}}\right)^{-\theta^k} \dot{Z}^k_{n,t+1} \tag{24}$$

$$X^k_{n,t+1} = \sum_{s=1}^{K} \gamma^{ks}_n \sum_{i=1}^{N} \lambda^k_{in,t+1} X^k_{i,t+1} + \alpha^k \left(\sum_{k=1}^{K} w^k_{n,t+1} L^k_{n,t+1} + \iota_n \chi_{t+1}\right) \tag{25}$$

$$w^k_{n,t+1} L^k_{n,t+1} = \gamma^k_n \left(1 - \psi^k\right) \sum_{i=1}^{N} \lambda^k_{in,t+1} X^k_{i,t+1} \tag{26}$$

for all regions n and i, industries k and s at each time t, where $\chi_{t+1} = \sum_{i=1}^{N} \sum_{s=1}^{K} \frac{\psi_i}{1-\psi_i} w^s_{i,t+1} L^s_{i,t+1}$ and the exogenous time changes in productivities $\dot{Z}_{t+1}$ are given by equation (11)*.*

Once we have the momentary equilibrium (i.e. production side of the economy) at each t using

[19] The intuition is that dynamic hat algebra behaves analogously to the differences-in-differences strategy in empirical microeconomics. Expressing the model in terms of changes relative to changes in a counterfactual economy differences out exogenous fundamentals. The changes over time act similarly to unit fixed effects and difference out time-invariant exogenous fundamentals. The change relative to the counterfactual economy acts like time fixed effects and differences out the time-trending exogenous fundamentals. This difference-in-differences-like methodology is what lets us simulate our model without quantifying or observing the exogenous fundamentals.

Proposition 1, we express the household side of the economy in time differences with the next proposition from CDP:

Proposition 2 (CDP). *Define* $u^k_{n,t} \equiv \exp(V^k_{n,t})$. *Given an initial allocation of the economy,* $(L_0, \pi_0, X_0, \pi_{-1})$ *and an anticipated convergent sequence of time changes in fundamentals,* $\{\dot{\mathbf{\Theta}}_{\mathbf{t}}\}_{t=1}^{\infty}$ *with* $\lim_{t\to\infty}\dot{\mathbf{\Theta}}_{\mathbf{t}} = 1$*, the solution to the sequential competitive equilibrium in time differences does not require information on the level of the fundamentals,* $\{\mathbf{\Theta}_{\mathbf{t}}\}_{t=0}^{\infty}$ *or* $\overline{\mathbf{\Theta}}$*. In particular, it is obtained as the solution to the following system of nonlinear equations:*

$$\dot{\pi}^{ks}_{ni,t+1} = \frac{\left(\dot{u}^s_{i,t+2}\right)^{\beta/\nu}}{\sum_{l=1}^{N}\sum_{h=0}^{K}\pi^{kh}_{nl,t}\left(\dot{u}^h_{l,t+2}\right)^{\beta/\nu}} \tag{27}$$

$$\dot{u}^k_{n,t+1} = \dot{B}_{n,t+1}\dot{\omega}^k_n(\dot{L}_{t+1}, \dot{Z}_{t+1}, \dot{\kappa}_{t+1})\left(\sum_{i=1}^{N}\sum_{s=0}^{K}\pi^{ks}_{ni,t}\left(\dot{u}^s_{i,t+2}\right)^{\beta/\nu}\right)^{\nu} \tag{28}$$

$$L^k_{n,t+1} = \sum_{i=1}^{N}\sum_{s=0}^{K}\pi^{sk}_{in,t}L^s_{i,t} \tag{29}$$

for all regions n *and* i*, industries* k *and* s *at each time* t*, where* $\{\dot{\omega}^k_n(\dot{L}_t, \dot{Z}_t, \dot{\kappa}_t)\}_{n=1,k=0,t=1}^{N,K,\infty}$ *is the sequence of real wages that solves the momentary equilibrium at each* t *given* $\{\dot{L}_{t+1}, \dot{Z}_{t+1}, \dot{\kappa}_{t+1}\}_{t=1}^{\infty}$*, and the exogenous time changes in amenities are given by the time changes of equation* (1)*, namely:* $\dot{B}_{n,t+1} = \dot{\bar{B}}_{n,t+1}\exp\left(f(\mathbf{T}_{n,t+1};\gamma) - f(\mathbf{T}_{n,t};\gamma)\right)$.

We are ultimately interested in counterfactual time changes in fundamentals under different climate scenarios relative to baseline time changes in fundamentals, i.e. hat variables $(\widehat{Y}_t)$. We use the following proposition to solve the model in terms of relative time changes so we can quantify the impacts of climate change:[20]

Proposition 3 (CDP). *Given a baseline economy,* $\{L_t, \pi_{t-1}, \lambda_t, X_t\}_{t=0}^{\infty}$*, and a convergent sequence of counterfactual changes in fundamentals,* $\left\{\widehat{\Theta}_t\right\}_{t=1}^{\infty}$ *with* $\lim_{t\to\infty}\widehat{\Theta}_t = 1$*, solving for the counterfactual sequential equilibrium* $\left\{L'_t, \pi'_{t-1}, \lambda'_t, X'_t\right\}_{t=1}^{\infty}$ *does not require information on the baseline fundamentals* $\left(\{\Theta_t\}_{t=0}^{\infty}, \bar{\Theta}\right)$*. In particular, the counterfactual sequential equilibrium can be obtained*

[20] Note that the proposition has different equilibrium conditions for the household problem at $t = 0$ because counterfactual migration flows at $t = 0$, ${\pi^{ks}_{ni,0}}'$, do not capture counterfactual changes in the option value at $t = 1$, since the trajectory of counterfactual fundamentals are only observed at $t = 1$. We thus have to replace $\frac{{\pi^{ks}_{ni,0}}'}{\pi^{ks}_{ni,0}}$ with $\left(\widehat{u}^s_{i,1}\right)^{\beta/\nu}$ in equilibrium conditions (30)-(31) for time $t = 0$.

from the following system of nonlinear equations:

$$\widehat{\pi}^{ks}_{ni,t+1} = \frac{\left(\widehat{u}^{s}_{i,t+2}\right)^{\beta/\nu}}{\sum_{l=1}^{N}\sum_{h=0}^{K}\pi^{kh}_{nl,t}{}'\dot{\pi}^{kh}_{nl,t+1}\left(\widehat{u}^{h}_{l,t+1}\right)^{\beta/\nu}} \tag{30}$$

$$\widehat{u}^{k}_{n,t+1} = \widehat{B}_{n,t+1}\widehat{\omega}^{k}_{n}\left(\widehat{L}_{t+1},\widehat{Z}_{t+1},\widehat{\tau}_{t+1}\right)\left(\sum_{i=1}^{N}\sum_{s=0}^{K}\pi^{ks}_{ni,t}{}'\dot{\pi}^{ks}_{ni,t+1}\left(\widehat{u}^{s}_{i,t+2}\right)^{\beta/\nu}\right)^{\nu} \tag{31}$$

$$L^{k}_{n,t+1}{}' = \sum_{i=1}^{N}\sum_{s=0}^{K}\pi^{sk}_{in,t}{}'L^{s}_{i,t}{}' \tag{32}$$

for all regions n and i, industries k and s at each time $t \geq 1$, where $\left\{\widehat{\omega}^{k}_{n}\left(\widehat{L}_{t+1},\widehat{Z}_{t+1},\widehat{\tau}_{t+1}\right)\right\}_{n=1,k=0,t=1}^{N,K,\infty}$ is the solution to the temporary equilibrium given $\left\{\widehat{L}_{t+1},\widehat{Z}_{t+1},\widehat{\tau}_{t+1}\right\}_{t=1}^{\infty}$, i.e. $\widehat{\omega}^{k}_{n}\left(\widehat{L}_{t+1},\widehat{Z}_{t+1},\widehat{\tau}_{t+1}\right)$ solves the following system of non-linear equations:

$$\widehat{x}^{k}_{n,t+1} = \left(\widehat{L}^{k}_{n,t+1}\right)^{\gamma^{k}_{n}\psi_{n}}\left(\widehat{w}^{k}_{n,t+1}\right)^{\gamma^{k}_{n}}\prod_{s=1}^{K}\left(\widehat{P}^{k}_{n,t+1}\right)^{\gamma^{ks}_{n}} \tag{33}$$

$$\widehat{P}^{k}_{n,t+1} = \left[\sum_{i=1}^{N}\lambda^{k}_{ni,t}{}'\dot{\lambda}^{k}_{ni,t+1}\widehat{Z}^{k}_{i,t+1}\left(\widehat{x}^{k}_{i,t+1}\widehat{\tau}^{k}_{ni,t+1}\right)^{-\theta^{k}}\right]^{\frac{1}{\theta^{k}}} \tag{34}$$

$$\widehat{\lambda}^{k}_{ni,t+1} = \left(\frac{\widehat{x}^{k}_{n,t+1}\widehat{\tau}^{k}_{ni,t+1}}{\widehat{P}^{k}_{n,t+1}}\right)^{-\theta^{k}}\widehat{Z}^{k}_{n,t+1} \tag{35}$$

$$X^{k}_{n,t+1}{}' = \sum_{s=1}^{K}\gamma^{ks}_{n}\sum_{i=1}^{N}\lambda^{k}_{in,t+1}{}'X^{k}_{i,t+1}{}' + \alpha^{k}\left(\sum_{k=1}^{K}w^{k}_{n,t+1}{}'L^{k}_{n,t+1}{}' + \iota_{n}\chi'_{t+1}\right) \tag{36}$$

$$w^{k}_{n,t+1}{}'L^{k}_{n,t+1}{}' = \gamma^{k}_{n}\left(1-\psi^{k}\right)\sum_{i=1}^{N}\lambda^{k}_{in,t+1}{}'X^{k}_{i,t+1}{}' \tag{37}$$

where $\chi'_{t+1} = \sum_{i=1}^{N}\sum_{s=1}^{K}\frac{\psi_i}{1-\psi_i}\dot{w}^{s}_{i,t+1}{}'\dot{L}^{s}_{i,t+1}{}'$. At time $t = 0$, however, the equilibrium conditions (30)-(31) *for the household migration problem should be replaced by:*

$$\widehat{\pi}^{ks}_{ni,1} = \frac{\left(\widehat{u}^{s}_{i,1}\right)^{\beta/\nu}\left(\widehat{u}^{s}_{i,2}\right)^{\beta/\nu}}{\sum_{i=1}^{N}\sum_{s=0}^{K}\pi^{ks}_{ni,1}\left(\widehat{u}^{s}_{i,1}\right)^{\beta/\nu}\left(\widehat{u}^{s}_{i,2}\right)^{\beta/\nu}} \tag{38}$$

$$\widehat{u}^{k}_{n,1} = \widehat{B}_{n,1}\widehat{\omega}^{k}_{n}\left(\widehat{L}_{1},\widehat{Z}_{1},\widehat{\tau}_{1}\right)\left(\sum_{i=1}^{N}\sum_{s=0}^{K}\pi^{ks}_{ni,1}\left(\widehat{u}^{s}_{i,1}\right)^{\beta/\nu}\left(\widehat{u}^{s}_{i,2}\right)^{\beta/\nu}\right)^{\nu}. \tag{39}$$

4.2 Simulating the Full Model

The previous three propositions show how our model structure allows us to solve for the equilibrium effects of climate change. In what follows we sketch the main steps to implement these three propositions and simulate the full model. Refer to Appendix C for more on the numerical algorithms, Appendix D for the data we use in the simulations, and Appendix E for construction of the climate shocks.

4.2.1 Historical Simulations

To recover the historical effect of temperature on the economy (in 2000–2014), we use a two step procedure:

Step 1: Solve the baseline economy with climate change and time-varying fundamentals in time changes We simulate the baseline economy with time-varying fundamentals from 2000–2014 using the sufficient statistics for the equilibrium variables in our model over that time period: trade flows, migration flows, and expenditures. We do not need to shock growth and amenities with climate effects in our baseline economy since they are already captured by the sufficient statistics data. For the household side, we obtain the trajectory of labor allocations using the observed data on migration shares and the initial labor allocation. After 2014, we simulate the economy forward until 2115 with constant fundamentals and no shocks to productivity or amenities, using the algorithm in time changes (CDP Propositions 1 and 2). This allows the effects of shocks to growth and amenities between 2000–2014 to fully unfold.

Step 2: Solve for proportional differences in baseline outcomes against outcomes in a counterfactual economy with time-varying fundamentals but without climate change, using the counterfactual algorithm We then solve our model in relative time changes, where the equilibrium outcomes are expressed as outcomes in the baseline economy with climate change against outcomes in a counterfactual economy without climate change. In the no climate change counterfactual, we hold the distribution of daily temperature is held constant at the initial year 2000 levels. We compute the relative time changes in productivity and amenities by shocking them with counterfactual climate shock relative to the actual climate shock. We then feed these relative time changes in fundamentals into the full counterfactual algorithm from CDP Proposition 3. The counterfactual model solution thus gives us the difference in outcomes with climate change relative to without, while also fully accounting for the real world unobserved fundamentals over the 2000–2014 time period due to the inclusion of the sufficient statistics data in Step 1.

4.2.2 Future Simulations

To determine the future impact of temperature in 2015–2100 we perform a similar exercise:

Step 1: Solve the baseline economy with climate change in time changes The primary difference for our future simulation is that we do not observe actual migration or trade flows and thus cannot fully capture all the time-varying fundamentals in our model with a small set of sufficient statistics. We instead assume that the time-varying fundamentals are held constant at their initial year 2015 value and use the numerical algorithm for constant fundamentals (from CDP Propositions 1 and 2) to solve the baseline economy.[21] Since we are not using sufficient statistics to capture the evolution of fundamentals, the baseline future economy does not implicitly capture the climate shocks and we must shock the baseline economy ourselves. We shock it with the benchmark SSP2-4.5 climate scenario, a middle-of-the-road scenario where CO_2 concentrations reach above 550ppm, and global average warming is about 2.5°C by end-of-century.

Step 2: Solve the counterfactual economy without climate change in time changes We then solve the counterfactual economy also in terms of time changes, where the distribution of daily temperature is held constant at 2015 levels and time-varying fundamentals are held constant at their year 2015 value. Step 2 is identical to Step 1 but with the counterfactual set of temperature distributions used to shock productivity and amenities.

Step 3: Compute counterfactual outcomes To compute the counterfactual outcomes i.e. the effects of climate change, we then divide the outcomes of our simulated baseline economy in Step 1 against their counterparts in our simulated counterfactual economy without climate change in Step 2 to construct the relative time difference variables.

4.3 Welfare Definition and Decomposition

We now define our measure of welfare and provide a heuristic analytical decomposition to highlight the role of different adaptation mechanisms in determining welfare. We define our welfare measure as the equivalent variation in consumption for households in market (n, k) in the initial period. Let primes denote variables under the counterfactual climate, the equivalent variation is the value of δ_n^k such that:

$$V_{n,0}^{k}{}' = \sum_{t=0}^{\infty} \beta^t \log \left(B_{n,t}' \frac{C_{n,t}^{k}{}'}{\left(\pi_{nn,t}^{kk}{}'\right)^{\nu}} \right)$$

$$V_{n,0}^{k}{}' = V_{n,0}^{k} + \sum_{t=0}^{\infty} \beta^t \log \left(\delta_n^k\right) = \sum_{t=0}^{\infty} \beta^t \log \left(B_{n,t} \frac{C_{n,t}^{k}}{\left(\pi_{nn,t}^{kk}\right)^{\nu}} \delta_n^k \right).$$

[21] An alternative would be to assume some trajectory of baseline productivity growth but we maintain constant productivity to focus on the impacts of temperature.

The consumption-equivalent change in welfare can then be computed using the relative time difference variables:

$$\begin{aligned}\log\left(\delta_n^k\right) &= \sum_{t=1}^{\infty}\beta^l \log\left(\widehat{B_{n,t}}\frac{\widehat{C_{n,t}^k}}{\left(\widehat{\pi_{nn,t}^{kk}}\right)^{\nu}}\right)\\ &= \sum_{t=1}^{\infty}\beta^t\left[\underbrace{\log\widehat{B_{n,t}}}_{\substack{\text{direct climate}\\ \text{impact on}\\ \text{amenities}}} \underbrace{-\,\nu\log\widehat{\pi_{nn,t}^{kk}}}_{\substack{\text{changes in}\\ \text{option value}}}+\underbrace{\log\widehat{w_{n,t}^k}-\log\widehat{P_{n,t}}}_{\text{changes in real wages}}\right].\end{aligned} \tag{40}$$

The first two terms capture climate impacts on utility, while the last term captures climate impacts on production. We can then decompose welfare into a set of exogenous and endogenous components:

$$\log\widehat{w_{n,t}^k} = \log\frac{\widehat{Y_{n,t}^k}}{\widehat{L_{n,t}^k}} = \underbrace{\log\widehat{Z_{n,t}^k}}_{\substack{\text{direct climate}\\ \text{impact on}\\ \text{productivity}}} \underbrace{-\,\theta^k\log\widehat{x_{i,t}^k}}_{\substack{\text{changes in}\\ \text{input costs}}} - \underbrace{\theta^k\log\widehat{\Lambda_n}}_{\substack{\text{changes}\\ \text{in firm}\\ \text{market access}}} - \underbrace{\log\widehat{L^{n,t}}}_{\substack{\text{changes in}\\ \text{labor}\\ \text{competition}}} \tag{41}$$

$$\log\widehat{P_{n,t}} = \log\left(\prod_{s=1}^{K}(\widehat{P_{n,t}^s})^{\alpha^s}\right) = \sum_{s=1}^{K}\alpha^s\log\widehat{P_{n,t}^s} = \underbrace{-\sum_{s=1}^{K}\frac{\alpha^s}{\theta^s}\log\widehat{\Phi_{n,t}^s}}_{\substack{\text{changes in consumer}\\ \text{market access}}} \tag{42}$$

where $\widehat{Y_{n,t}^k} \equiv \sum_{i=1}^N \lambda_{in,t}X_{i,t}$, $\Lambda_{n,t}^{-\theta^k} \equiv \sum_{i=1}^N \frac{(\tau_{in,t})^{-\theta^k}X_{i,t}}{\Phi_{i,t}^k}$, and $\Phi_{i,t}^k \equiv \sum_{l=1}^N Z_{l,t}^k\left(x_{l,t}^k\tau_{il,t}^k\right)^{-\theta^k}$.

The terms in equations (40)-(42) highlight the different spatial channels in which climate shocks are transmitted through our economy, as well as the role of different adaptation mechanisms. For example, welfare changes from amenities are caused by exogenous changes in local temperature and endogenous migration responses, while welfare changes from nominal wages are driven by exogenous productivity changes, and endogenous changes in prices and labor allocation. Note that changes in endogenous wages and prices capture contemporaneous adaptation channels, while changes in option value capture the dynamic adaptation channel of migration across labor markets.

4.4 Quantitative Decomposition of Adaptation Mechanisms

To quantify the effect of different economic channels and market-based adaptation, we then conduct simulations in which we shut down or fix different parts of the model. Quantifying the role of different economic channels in magnifying or dampening the effect of climate change is relatively straightforward because these are changes to exogenous attributes of the model. To remove input-output loops, we set the shares of intermediates in production equal to zero: $\gamma_n^{ks} = 0$ for all n and s. To remove local structures we set the structures share of value added equal to zero: $\psi^k = 0$ for all k. To remove amenities, we set $B_{n,t} = 1$ in the utility function for all realizations of temperature. We then run simulations with different combinations of economic channels turned off and recompute the effects of climate change.

Identifying the role of adaptation through trade, migration across locations, and industry switching is more complex. For example, to understand the value of adaptation through trade we cannot simply solve the model under autarky since autarky is not the right counterfactual comparison. The proper counterfactual is a world where trade still occurs, but does not adjust in response to climatic shocks. Here we describe our new approach to decompose the benefits of market-based adaptation in response to arbitrary shocks to any economic fundamentals. The key step is that in our simulations with climate change, we fix trade shares, migration shares across regions, and industry switching shares to their trajectories derived from an identical model that was not affected by climate change. This eliminates adaptation in response to climate change along each channel without completely shutting down movement of goods and labor. We compare the results from these constrained simulations against the results from the simulations described earlier where all the adaptation channels are active. The difference between the two gives us the impacts of adaptation through trade and the labor market. In what follows we present the theoretical basis of our approach and detail the adjustments required to our solution algorithms for the full model described above. Note that for our quantitative identification of adaptation channels we focus on the forward simulation.

4.4.1 Identifying Trade Adaptation

We formally identify the role of trade adaptation with the following proposition.

Proposition 4. *Suppose that the exogenous trajectories of trade shares $\{\overline{\lambda}_t\}_{t=0}^{\infty}$ and the time changes in productivities $\{\dot{Z}_t\}_{t=0}^{\infty}$ and trade costs $\{\dot{\tau}_t\}_{t=0}^{\infty}$ are known. Then given the time-t momentary equilibrium allocation $\{L_t, X_t\}$, the solution to the time-t+1 momentary equilibrium $\{L_{t+1}, X_{t+1}\}$* ***without trade adjustment*** *can be obtained from the following system of nonlinear equations:*

$$\dot{x}_{n,t+1}^k = \left(\dot{L}_{n,t+1}^k\right)^{\gamma_n^k \psi_n} \left(\dot{w}_{n,t+1}^k\right)^{\gamma_n^k} \prod_{s=1}^{K} \left(\dot{P}_{n,t+1}^k\right)^{\gamma_n^{ks}}, \tag{43}$$

$$\dot{P}_{n,t+1}^k = \left[\sum_{i=1}^{N} \overline{\lambda}_{ni,t}^k \dot{Z}_{i,t+1}^k \left(\dot{x}_{i,t+1}^k \dot{\tau}_{ni,t+1}^k\right)^{-\theta^k}\right]^{\frac{1}{\theta^k}}, \tag{44}$$

$$X_{n,t+1}^k = \sum_{s=1}^{K} \gamma_n^{ks} \sum_{i=1}^{N} \overline{\lambda}_{in,t+1}^k X_{i,t+1}^k + \alpha^k \left(\sum_{k=1}^{K} \dot{w}_{n,t+1}^k \dot{L}_{n,t+1}^k w_{n,t}^k L_{n,t}^k + \iota_n \chi_{t+1}\right), \tag{45}$$

$$w_{n,t+1}^k L_{n,t+1}^k = \gamma_n^k \left(1 - \psi^k\right) \sum_{i=1}^{N} \overline{\lambda}_{in,t+1}^k X_{i,t+1}^k, \tag{46}$$

where $\chi_{t+1} = \sum_{i=1}^{N} \sum_{s=1}^{K} \frac{\psi_i}{1-\psi_i} w_{i,t+1}^s L_{i,t+1}^s$.

For a given set exogenous trajectories of *time* changes in fundamentals, Proposition 4 together with Proposition 2 (CDP) allow us to generate equilibrium trajectories of the economy without trade shares changing endogenously. In our results, we fix the exogenous trajectory of trade shares equal to the equilibrium trade shares from the full unconstrained model (Propositions 1 and 2) without climate change, however they could be set to any arbitrary trajectory. Comparing the equilibrium outcomes of this trade share-constrained economy shocked by climate change against the outcomes from the full unconstrained model shocked by climate change allows us to determine the role of adjustment through trade.

4.4.2 Identifying Migration Adaptation

To identify adaptation in migration across regions and industry switching, we decompose migration shares across markets as follows:

$$
\begin{aligned}
\pi_{ni,t}^{ks} &= \frac{\sum_{h=0}^{K} \exp\left[\left(\beta \mathbb{E}_t\left(V_{i,t+1}^{h}\right) - \mu_{ni}^{kh}\right)/\nu\right]}{\sum_{l=1}^{N}\sum_{h=0}^{K} \exp\left[\left(\beta \mathbb{E}_t\left(V_{l,t+1}^{h}\right) - \mu_{nl}^{kh}\right)/\nu\right]} \cdot \frac{\exp\left[\left(\beta \mathbb{E}_t\left(V_{i,t+1}^{s}\right) - \mu_{ni}^{ks}\right)/\nu\right]}{\sum_{h=0}^{K} \exp\left[\left(\beta \mathbb{E}_t\left(V_{i,t+1}^{h}\right) - \mu_{ni}^{kh}\right)/\nu\right]} \\
&= \underbrace{\pi_{ni,t}^{k}}_{\substack{\text{migration} \\ \text{across regions}}} \cdot \underbrace{\pi_{ni,t}^{ks}|\pi_{ni,t}^{k}}_{\text{industry switching}}
\end{aligned}
$$

where $\pi_{ni,t}^{k} \equiv \sum_s \pi_{ni,t}^{ks}$ is the migration share across regions ni for workers originally in industry k, and $\pi_{ni,t}^{ks}|\pi_{ni,t}^{k} \equiv \frac{\pi_{ni,t}^{ks}}{\pi_{ni,t}^{k}}$ is the industry-switching share across industries ks amongst workers who were originally in industry k and migrated from region n to region i. Given this decomposition, we identify the role of adaptation in migration across regions and industry switching using the following proposition.

Proposition 5. *(i) Suppose that the exogenous trajectories of migration across regions $\{\pi_t^k\}_{t=0}^{\infty}$ and the time changes in fundamentals are known. Then the sequential competitive equilibrium in **time changes without adjustment in migration across regions** can be obtained from the following system of nonlinear equations:*

$$
\dot{\pi}_{ni,t+1}^{ks} = \dot{\bar{\pi}}_{ni,t+1}^{k} \frac{\left(\dot{u}_{n,t+2}^{k}\right)^{\beta/\nu}}{\sum_{h=0}^{K} \pi_{ni,t}^{kh}\left(\dot{u}_{l,t+2}^{h}\right)^{\beta/\nu}} \tag{47}
$$

$$
\dot{u}_{n,t+1}^{k} = \dot{B}_{n,t+1}\dot{\omega}_n^k(\dot{L}_{t+1}, \dot{Z}_{t+1}, \dot{\kappa}_{t+1}) \left(\sum_{i=1}^{N}\sum_{s=0}^{K} \pi_{ni,t}^{ks}\left(\dot{u}_{i,t+2}^{s}\right)^{\beta/\nu}\right)^{\nu} \tag{48}
$$

$$
L_{n,t+1}^{k} = \sum_{i=1}^{N}\sum_{s=0}^{K} \pi_{in,t}^{sk} L_{i,t}^{s} \tag{49}
$$

where $\{\dot{\omega}_n^k(\dot{L}_t, \dot{Z}_t, \dot{\kappa}_t)\}_{n=1,k=0,t=1}^{N,K,\infty}$ is the sequence of real wages that solves the momentary equilibrium (production side) in time changes given $\{\dot{L}_{t+1}, \dot{Z}_{t+1}, \dot{\kappa}_{t+1}\}_{t=1}^{\infty}$ [equations (22)-(26)], and the exogenous time changes in amenities are given by the time changes of equation (1)*.*

(ii) Given exogenous trajectories of industry switching $\{\pi_{ni,t}\}_{t=0}^{\infty}$ and time changes in fundamentals, the sequential equilibrium in ***time*** *changes* ***without adjustment in industry switching*** *can be obtained by replacing equation (47) in (i) with:*

$$\dot{\pi}_{ni,t+1}^{ks} = \frac{\sum_{h=0}^{K} \pi_{ni,t}^{kh} \left(\dot{u}_{l,t+2}^{h}\right)^{\beta/\nu}}{\sum_{l=1}^{N} \sum_{h=0}^{K} \pi_{nl,t}^{kh} \left(\dot{u}_{l,t+2}^{h}\right)^{\beta/\nu}} \cdot \dot{\overline{\pi_{ni,t}^{ks}|\pi_{ni,t}^{k}}}. \tag{50}$$

For a given set exogenous trajectories of time changes in fundamentals, Proposition 5 generates equilibrium trajectories of the economy without the shares of migration across regions or shares of industry switching changing endogenously. While the exogenous shares for migration across regions or industry switching can be set to any arbitrary path, we set them to the path from the full model solution without climate change in our main results, following our method for isolating trade adaptation in the forward simulations described after Proposition 4. Comparing the equilibrium outcomes of this migration or industry switching-constrained economy against the outcomes from the full unconstrained model, allows us to determine the role of adjustment in only migration or only industry switching.

Given Proposition 5, we can also examine the role of labor market adjustment across all markets (migration across regions and industry switching combined) using the following corollary:

Corollary 1. *Suppose that the trajectories of exogenously given migration shares $\{\overline{\pi}_t\}_{t=0}^{\infty}$, time changes in productivities $\{\dot{Z}_t\}_{t=0}^{\infty}$, and time changes in trade costs $\{\dot{\tau}_t\}_{t=0}^{\infty}$ are known. Then the sequential competitive equilibrium in* ***time*** *changes* ***without labor market adjustment*** *is given by the sequence $\{\dot{\omega}_{n,t}^{k}\left(\dot{\overline{L}}_t, \dot{Z}_t, \dot{\tau}_t\right)\}_{t=0}^{\infty}$ that solves equations (22)-(26) at each time t, where the exogenous trajectory of $\dot{\overline{L}}_t$ is constructed from the trajectory of baseline migration shares given.*

In this corollary, the intertemporal decisions of the household become completely exogenous because migration shares and industry switching are both made exogenous. With Proposition 5 and Corollary 1, we can quantify the role of adaptation in industry switching, migration across regions, or in both, without restricting the model to be one with no labor movement at all but rather one in which labor movement is restricted to the path it would have taken in the absence of climate change. More details on our quantitative procedures to identify the impact of each adaptation channel can be found in Appendix E.

4.5 Decomposing the Effect of Heterogeneity

In addition to decomposing the effects of market adaptation we also decompose the effects of heterogeneity in how climate change affects different industries and how the distribution of temperature changes over time and across space. To identify the role industrial heterogeneity plays in our model, we run simulations with the average response function imposed on all industries. The average response function comes from estimating equation (17), but without any industry dummy interactions. Next we identify the role of within-year temperature variability on equilibrium outcomes in the economy. We do so in two steps. First, we run simulations where the distribution of daily temperature is held constant at its year 2015 level, shutting down heterogeneous changes in future temperature variability. Second, we run simulations where the within-year temperature distribution is collapsed down to the mean daily temperature which eliminates all temperature variability from the model, similar to approaches that only use mean temperature. We expect these forms of heterogeneity to interact with adaptation because heterogeneity affects comparative advantage across regions and industries, and leads to changes in the relative attractiveness of different locations in terms of amenities and real wages.

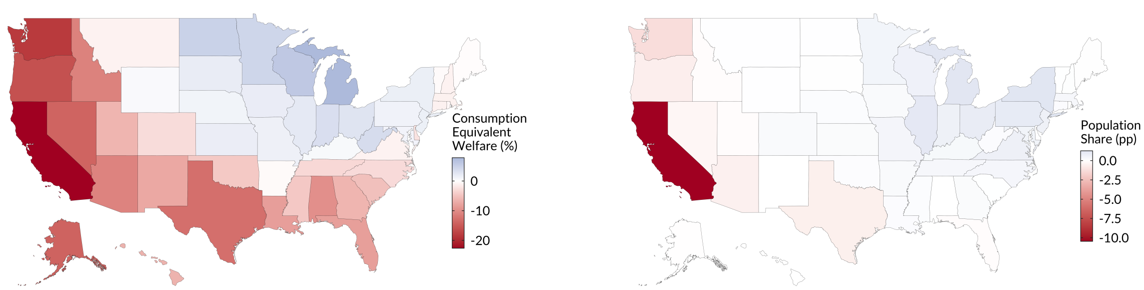
5 Quantitative Results

We now present our quantitative results for the historical and future simulations. We first show the quantitative results from the full model. We then decompose the role of different economic channels, the effects of market-based adaptation, and the interaction of adaptation with industry and climatic heterogeneity.

5.1 The Full Impacts of Climate Change

5.1.1 Historical Effects of Climate Change: 2000–2014

Figure 2: US welfare and population effects: 2000–2014.



Note: The left panel shows the welfare impact of climate change as a percent of consumption averaged over the households in each state at the initial year. The right panel shows the difference between state employment shares in the baseline economy with climate change for 2000-2014, and simulated state employment shares in a counterfactual scenario where the annual temperature distribution for each location was held constant at its 2000 level for 2000–2014, at the final time period for the simulations. Both the baseline and counterfactual are simulated for 2015–2115 with constant fundamentals ($\dot{Z}^k_{i,t} = 1$ for all i, k), and no climate change, to allow the full impacts of the shocks to unfold. Both maps correspond to our full model with productivity shocks, amenity shocks, local structures, input-output loops, and heterogeneous response functions across industries.

Figure 2 shows the impact of temperature changes from 2000–2014 on welfare and population in each state in the US, while fully accounting for all time-varying fundamentals. As shown in Section 4.3, the welfare effects are interpreted as the permanent gain in consumption for those living in a particular location in the initial period of the model. The historical results use climate shocks from 2000–2014, and then simulate an additional 100 years without climate change since reallocation may take time to unfold due to adjustment costs in migration and industry switching. Refer to Appendix E for more details. Warming over the 2000–2014 time period had heterogeneous effects, with large losses in the west and gains in the Midwest. The large losses in the West are primarily due to worsened amenities over this timeframe. On average, the US population experienced a welfare loss of 5.4% due to impacts on growth and amenities, but these effects were highly heterogeneous.

In response to heterogeneous climate impacts, households reallocated across states by migrating. Allowing population shares to adjust until year 2115, climate change from 2000-2014 would result in state population shares decreasing across the West, and by 10 percentage points in California compared to a world without climate change. The decline in California's population is largely driven by its population slightly decreasing with climate change versus growing significantly in a world without climate change. California experienced extremely hot years during this timeframe, particularly 2012 and 2014, inhibiting households in other states from migrating to California due to worsened amenities and long-run reductions in productivity from reduced growth. Population losses in the West are offset by population increases in the Midwest and East with the largest gains in New York, Michigan, and Illinois.

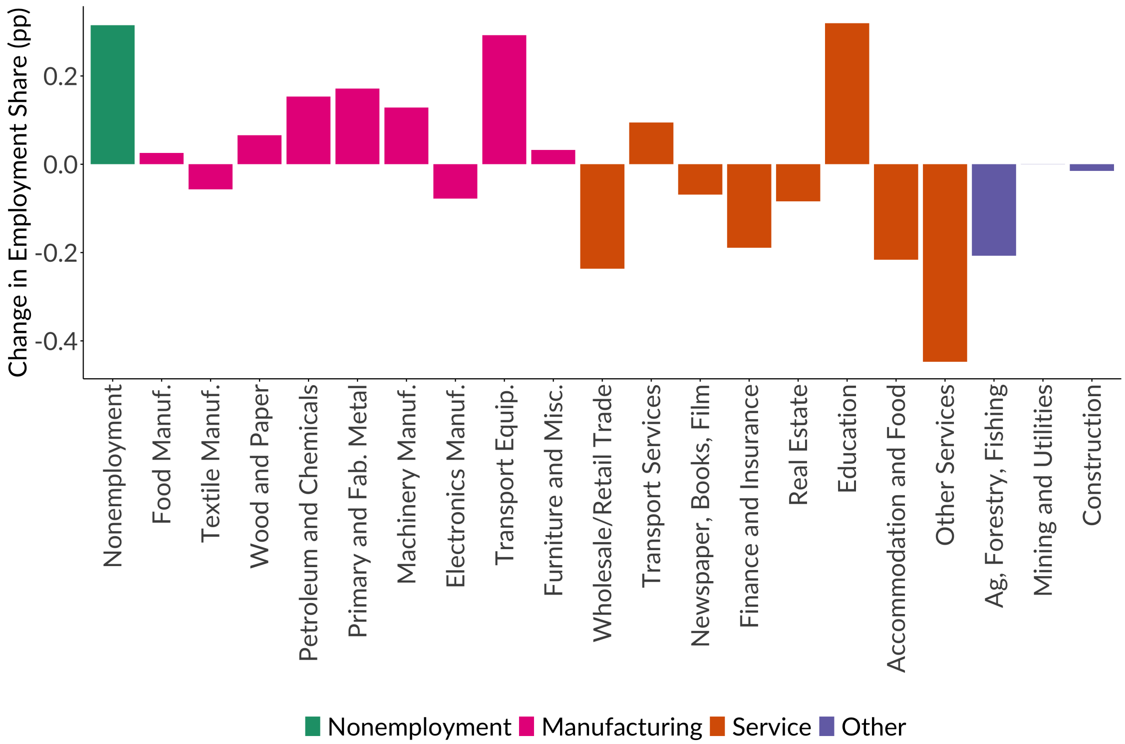
Figure 3 shows how climate change affected worker reallocation across US industries, where nonemployment is in green, manufacturing sector industries are in pink, service sector industries are in orange, and all others are in purple. Overall, climate change led to an increase in nonemployment and mixed results for other sectors. Education and several manufacturing industries had the greatest employment increases of 0.1–0.2 percentage points, while the services sector and agriculture, forestry, and fishing had substantial losses of employment.

Figure 4 shows the welfare impact of temperature changes in all non-US countries. Most countries are worse off by about 10% with some Northern European countries experiencing even larger losses. Climate change over this period reduced global welfare by 4.6%.

5.1.2 Future Effects of Climate Change: 2015–2100

We now turn to the projected future effects of climate change, captured by the projected changes in US temperature distributions from 2015–2100 presented in Figure 5. Figure 5 shows the change in the distribution of daily temperature for each state from the first ten years of our climate simulation (2015–2024) to the last ten years (2091–2100). Each graph shows the state's increase in number of days per year in each temperature bin, and the vertical line denotes the peak of the aggregate productivity response curve. From the figure we can see that Alaska experiences a significant decrease in extreme cold days that are offset by more moderate days near the peak for productivity growth. Maine, another cold state, also experiences a decline in extreme cold days, however these tend to be offset by hot days rather than moderate days. States in the Pacific Northwest have less stark changes in their temperature distributions, while states in the South trade cool and

Figure 3: US industry employment effects: climate shocks during 2000–2014.

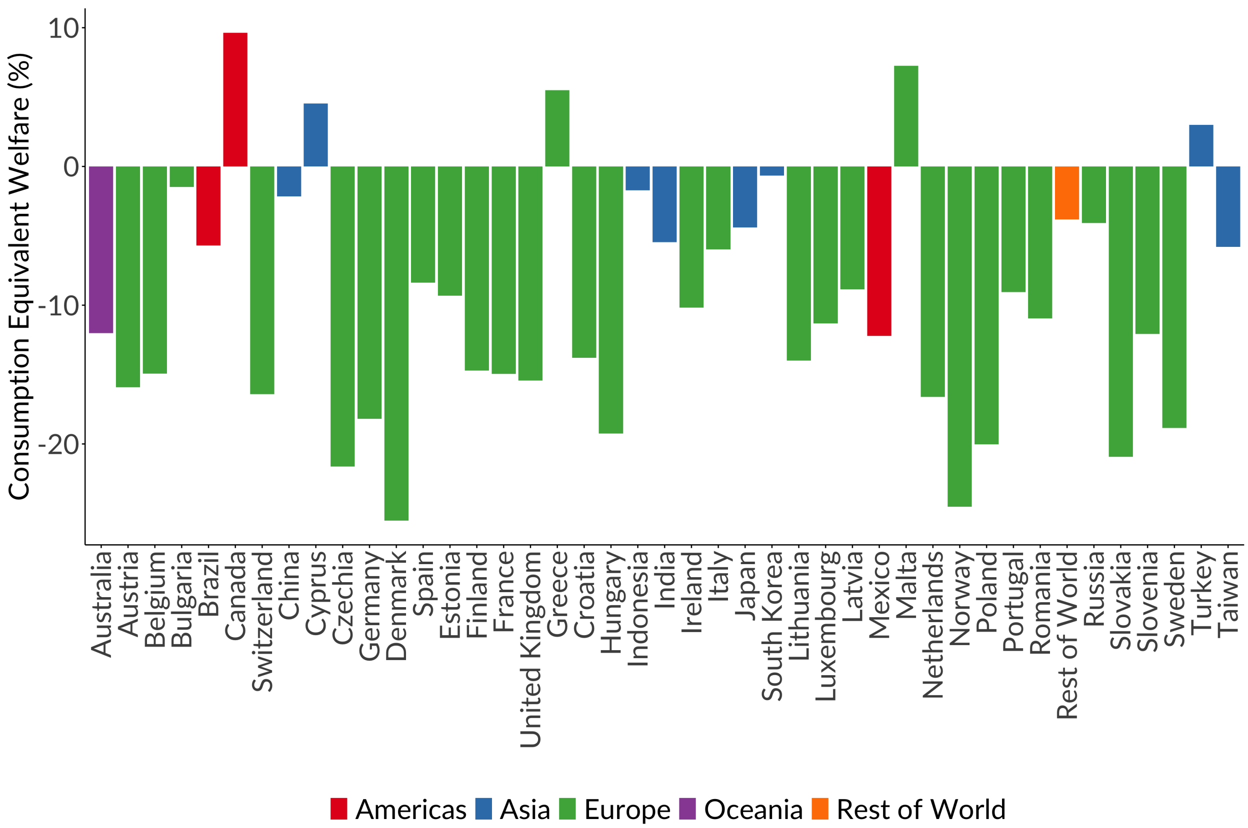


Note: The units are the changes in employment shares of each industry relative to a counterfactual scenario where the annual temperature distribution for each location was held constant at its 2000 level for 2015–2115. The units are the fraction of total US population so total population sums to 1 and the total change sums to zero. Both the baseline and counterfactual are simulated for 2100–2115 with constant fundamentals ($\dot{Z}_{i,t}^{k} = 1$ for all i, k), and no climate change, to allow the full impacts of the shocks to unfold. The results are from our full model with productivity shocks, amenity shocks, local structures, input-output loops, and heterogeneous response functions across industries.

moderate days for additional extremely hot days above 30°C.[22] These distributional changes lead to changes in within-year temperature variability as shown in Figure A6 in the Appendix. 40 states are expected to have increased temperature variability. The largest increases in variability tend to be in Midwestern states, while the largest decreases are in Southern states and Alaska. There are ten states with variability increases that are larger in absolute magnitude than the state with the largest variability decrease.

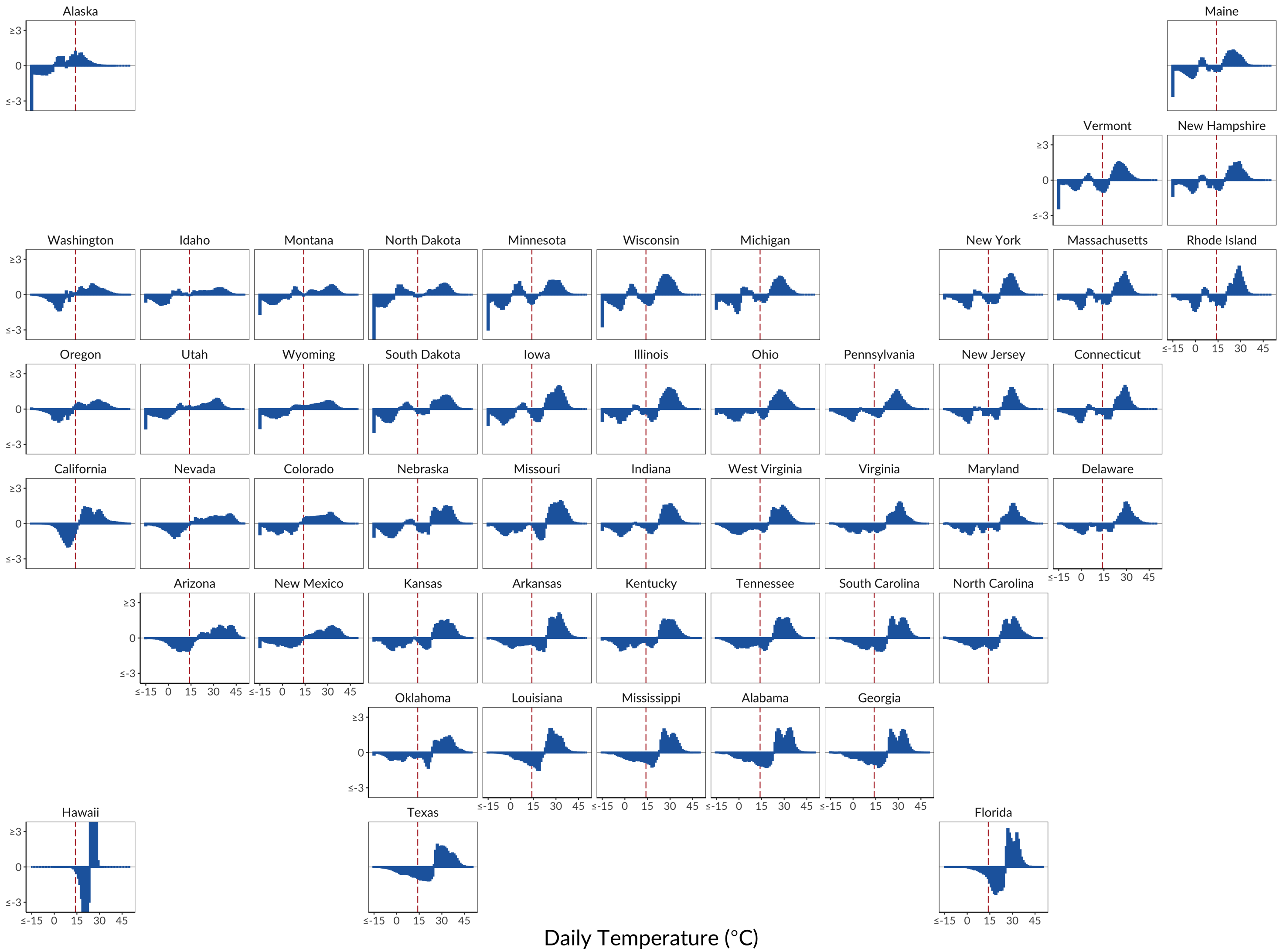
[22]Figure A6 in the Appendix shows the distribution of changes in temperature variances across states and countries from 2015–2024 to 2091–2100.

Figure 4: Non-US welfare effects: climate shocks during 2000–2014.



Note: The counterfactual scenario is if the annual temperature distribution for each location was held constant at its 2000 level for 2000–2014. Both the baseline and counterfactual are simulated for 2015–2115 with constant fundamentals ($\dot{Z}^k_{i,t} = 1$ for all i, k), and no climate change, to allow the full impacts of the shocks to unfold. All non-US countries have no migration or industry switching due to data limitations on the labor distribution, and they do not have welfare impacts from amenities since the amenity response function was estimated on US data at the state level.

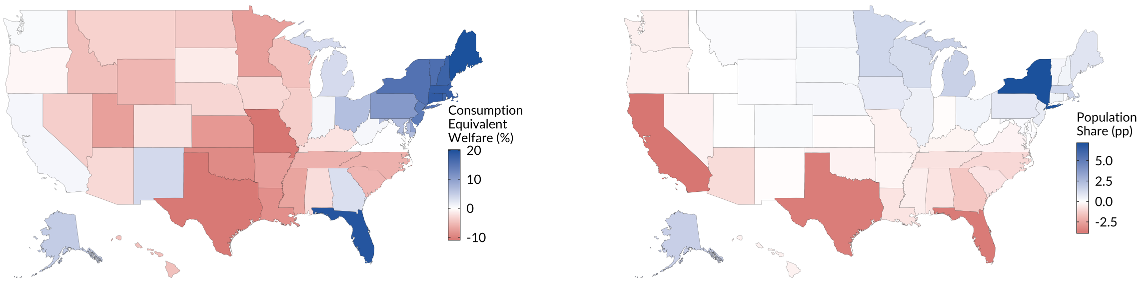
Figure 5: Change in within-year state temperature distributions: 2015–2024 to 2091–2100.



Note: Each plot shows the state-specific change in the number of days in each 1°C temperature bin from the first ten years (2015–2024) to last ten years (2090–2099) of the SSP2-4.5 climate scenario. Positive numbers denote increases in days at that temperature, negative numbers denote decreases. The temperature distributions are Windsorized at -15°C and 50°C. The vertical red dashed line corresponds to the optimal daily temperature for aggregate productivity growth.

30

Figure 6: US welfare and population effects: climate shocks during 2015–2100.



Note: The left panel shows the welfare impact of climate change as a percent of consumption averaged over the households in each state at the initial year. The right panel shows the difference between state employment shares in the baseline economy with climate change for 2015-2100, and simulated state employment shares in a counterfactual scenario where the annual temperature distribution for each location was held constant at its 2015 level for 2015–2100, at the final time period for the simulations. Both the baseline and counterfactual are simulated for 2101–2200 with constant fundamentals ($\dot{Z}_{i,t}^k = 1$ for all i, k) to allow the full impacts of the shocks to unfold. Both maps correspond to our full model with productivity shocks, amenity shocks, local structures, input-output loops, and heterogeneous response functions across industries.

Figure 6 shows the effects of future climate change on US states' welfare and population.[23] Around half of US states experience welfare losses from climate change through the end of the century, but the population-weighted average effect is a gain of 1.6%. The largest welfare gains are in the Northeast US and Florida. In response to the heterogeneous impacts across space, households migrate from the South and West to the Midwest and Northeast.[24] The shares of the population in Wisconsin, Michigan, and Minnesota are expected to grow by 0.5 percentage points due to climate change, while New York's share of the population will grow by 5 percentage points. Households are largely migrating out of populous southern states such as Florida and Texas, as well as California, all of which experience population share losses of over 2 percentage points.

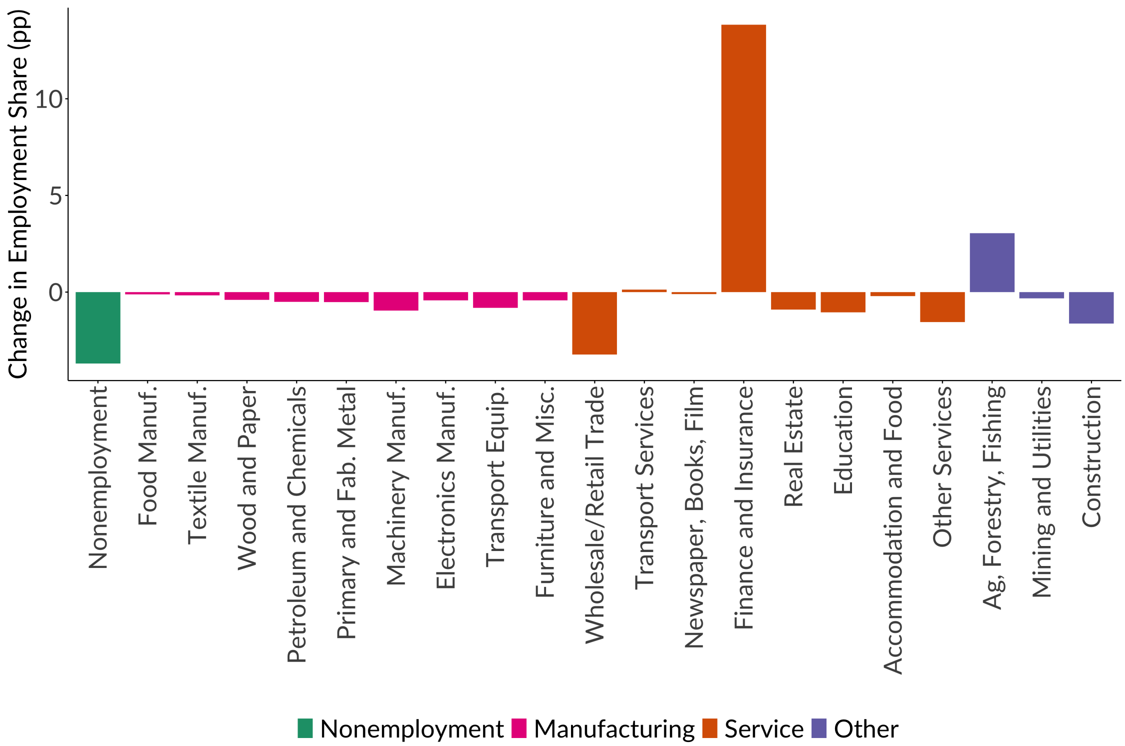
Figure 7 shows US industry reallocation under climate change. First, we project an overall increase in labor supply by 4 percentage points. We project substantial increases in the employment shares in the agriculture, forestry, and fishing industries, as well as finance and insurance. All other industries have declines in employment shares or near-zero effects, with relatively uniform effects across manufacturing industries. These results suggest that future climate change will reinforce the decline of manufacturing in the US.

Figure 8 shows the welfare impacts on non-US countries. Virtually all non-US countries are worse off. The only countries experiencing large gains are at high latitudes, and Taiwan. Significant losses occur in large countries such as Brazil and India, as well as our representation of the Rest of the World. The population-weighted global impact of climate change is a welfare loss of 10.9%.

[23]Figure A3 in the Appendix shows the effects of future climate change under standard assumptions implicit in the empirical literature: no input-output loops, homogeneous damages across industries, no amenity effects, and no adjustments through trade, migration, nor industry switching.

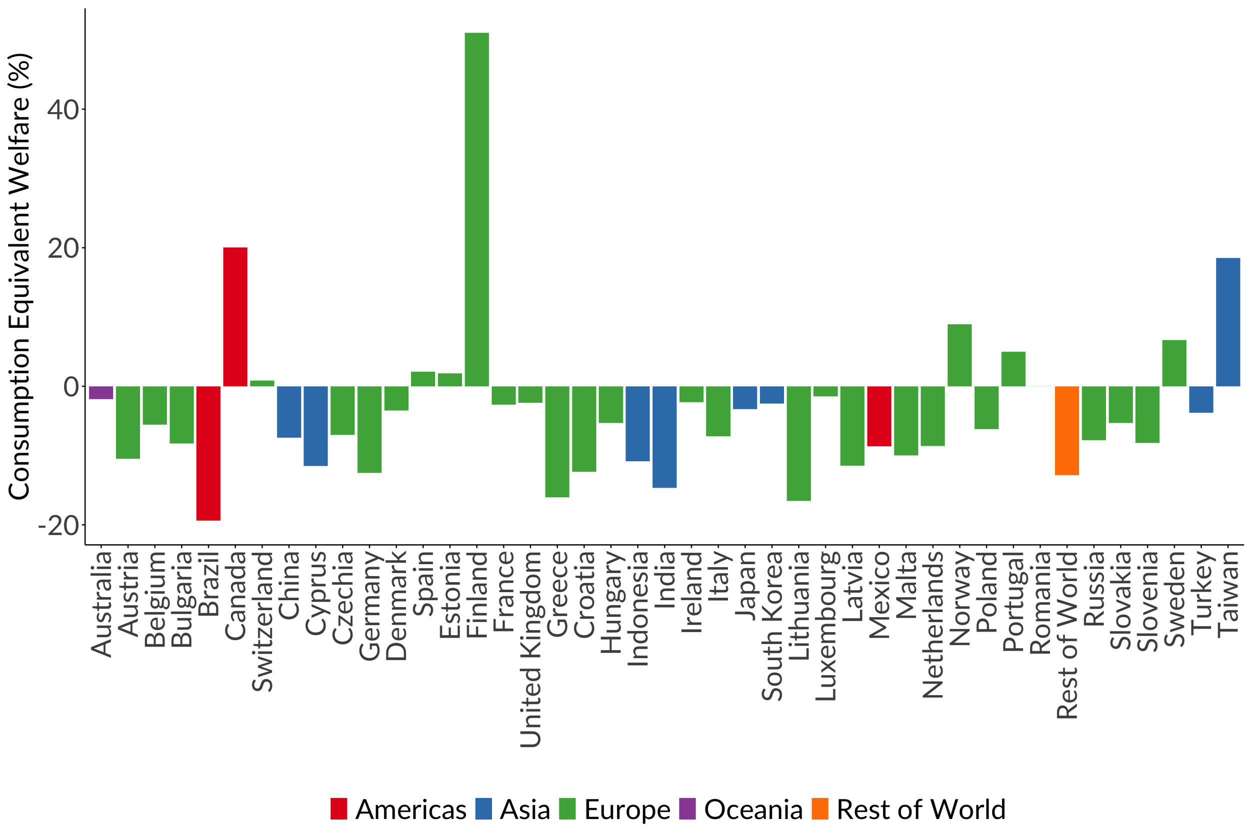
[24]Florida has an increase in welfare for incumbent households and out-migration because Florida incurs significant welfare losses near the end of the century which induces out-migration, but the welfare effects are small in present value terms.

Figure 7: US industry employment effects: climate shocks during 2015–2100.



Note: The units are the changes in levels of employment of each industry relative to no counterfactual. The units are the fraction of total US population so total population sums to 1 and the total change sums to zero. The counterfactual scenario is if the annual temperature distribution for each location was held constant at its 2015 level for 2015–2100. Both the baseline and counterfactual are simulated for 2101–2200 with constant fundamentals ($\dot{Z}^k_{i,t} = 1$ for all i, k) to allow the full impacts of the shocks to unfold. The results are from our full model with productivity shocks, amenity shocks, local structures, input-output loops, and heterogeneous response functions across industries.

Figure 8: Non-US welfare effects: climate shocks during 2015–2100.



Note: The counterfactual scenario is if the annual temperature distribution for each location was held constant at its 2015 level for 2015–2100. Both the baseline and counterfactual are simulated for 2101–2200 with constant fundamentals ($\dot{Z}^k_{i,t} = 1$ for all i, k) to allow the full impacts of the shocks to unfold. All non-US countries have no migration, and costless industry switching due to data limitations on the labor distribution, and they do not have welfare impacts from amenities since the amenity response function was estimated on US data at the state-level.

5.2 The Role of Different Economic Channels

We now decompose how the structure of the economy matters for the effects of climate change. We compute the welfare impact of different model attributes by simulating models omitting one of these attributes, and then comparing the welfare results relative to those from our full model. We focus on novel attributes of our model that are often omitted from simulations in the microeconometric and macroeconomics literature. Recall that δ_n^k denotes our consumption-equivalent change in welfare for market (n, k) from equation (40), and let δ be the population-weighted average of all δ_n^k's in the US in our full model results shown in Figures 2 and 6. Let δ^{-A} denote the welfare effect of climate change from a model with attribute A omitted. Our measure of change in welfare from properly accounting for attribute A is:

$$\Delta^A := \delta - \delta^{-A}.$$

We first present results in Table 1 on model attributes not directly related to trade, migration, or industry switching. Each row in Table 1 reports Δ^A for a different attribute A. The second row shows the welfare effect of input-output loops introduced by intermediates in production. Recall that the aggregate US welfare effect in our full model was -5.4% for the historical simulations, and 1.6% in the future simulations. Climate effects through input-output linkages decreased welfare by 1.3pp in the historical simulations, and increased welfare by 8.7pp in the future simulations. The third row shows that structures and input-output loops combined tend to improve welfare both historically and in the future. The fourth row shows that climate impacts on local US amenities worsen welfare, and are a major determinant of the magnitude of welfare impacts. The fifth row shows the effect of replacing the industry-specific temperature response functions with the average response function plotted in Figure 1. This has little effect on historical welfare, but industry heterogeneity is the primary determinant of US welfare in the future simulation. US welfare in a model without industrial heterogeneity would be -16.8% instead of a gain of 1.6%.

The last two rows of Table 1 show the effects of temperature variability. The second-to-last row reports the change in US welfare with respect to changes in temperature variability over time. We fix variability over time by replacing each year Y's temperature distribution with the initial year's temperature distribution, denoted Y_0, but where Y_0 is shifted so that the median matches the true temperature median in year Y. This preserves the shape and variability of the distribution while allowing the mean and median to change over time, and for variability to be heterogeneous across regions even though it is time-invariant. Changes in temperature variability alone accounts for a reduction in welfare of 3.6 percentage points in the historical period, and 12.2 percentage points in the future simulation. These losses are because most US states and countries are projected to experience an increase in temperature variability as shown in Figure A6 in the Appendix. The last row shows the value of representing all within-year temperature variability. We compute this value by simulating a model where a region's daily temperature is always equal to the mean daily temperature in that year, similar to approaches using only annual mean temperature. The full effect of temperature variability is a reduction in welfare of 2.5 and 8.5 percentage points. These

Table 1: US welfare contribution of model attributes.

	Historical (2000–2014)	Future (2015–2100)
Value of IO Loops	-1.3pp	8.7pp
Value of IO Loops and Structures	6.4pp	7.3pp
Value of Amenities	-2.7pp	-13.4pp
Value of Industry Heterogeneity	-0.7pp	18.4pp
Value of Time Variation in Daily Temperature Variability	-3.6pp	-12.2pp
Value of All Temperature Variability	-2.5pp	-8.5pp

Note:
Each row shows the difference in welfare between our full model and a model without the listed attribute.

results show that proper representation of the general equilibrium properties of the economy, direct effects of climate change on utility, and accounting for both industrial and climatic heterogeneity are first-order concerns. The welfare effects of these attributes is the same order of magnitude as the total welfare effect, and their inclusion can change the sign of the welfare impacts of climate change.

5.3 Benefits of Market-Based Adaptation

We now quantify the benefits of market-based adaptation. We focus on the future simulations and consider three endogenous responses to changes in climate: changing trade shares, changing migration shares, and changing industry switching shares. As explained in Section 4.4 and Appendix E, we quantify the role of adaptation by holding each adaptation mechanism fixed to their levels in our counterfactual model simulation without climate change, and then compare against outcomes from our full model.

Table 2 reports welfare values Δ^A for the three adaptation mechanisms. Each column shows the difference in welfare from our full model relative to models where we turn off different combinations of adaptation mechanisms. All three adaptation channels combined improve welfare by 13.7pp, turning a loss of 12.1% into a gain of 1.6% as reported in Table 1. Adaptation through changing trade shares alone improves welfare by 12.9pp, and can account for almost all of the combined gains from adaptation. Changes in industry switching shares improves welfare by 3.1pp, while changes in within-US migration has the smallest effect, improving welfare by only 1.1pp.[25] Adaptation through both labor market mechanisms improves welfare by 3.9pp. The combination of adaptation mechanisms is subadditive, indicating that there is substitutability between all three mechanisms.

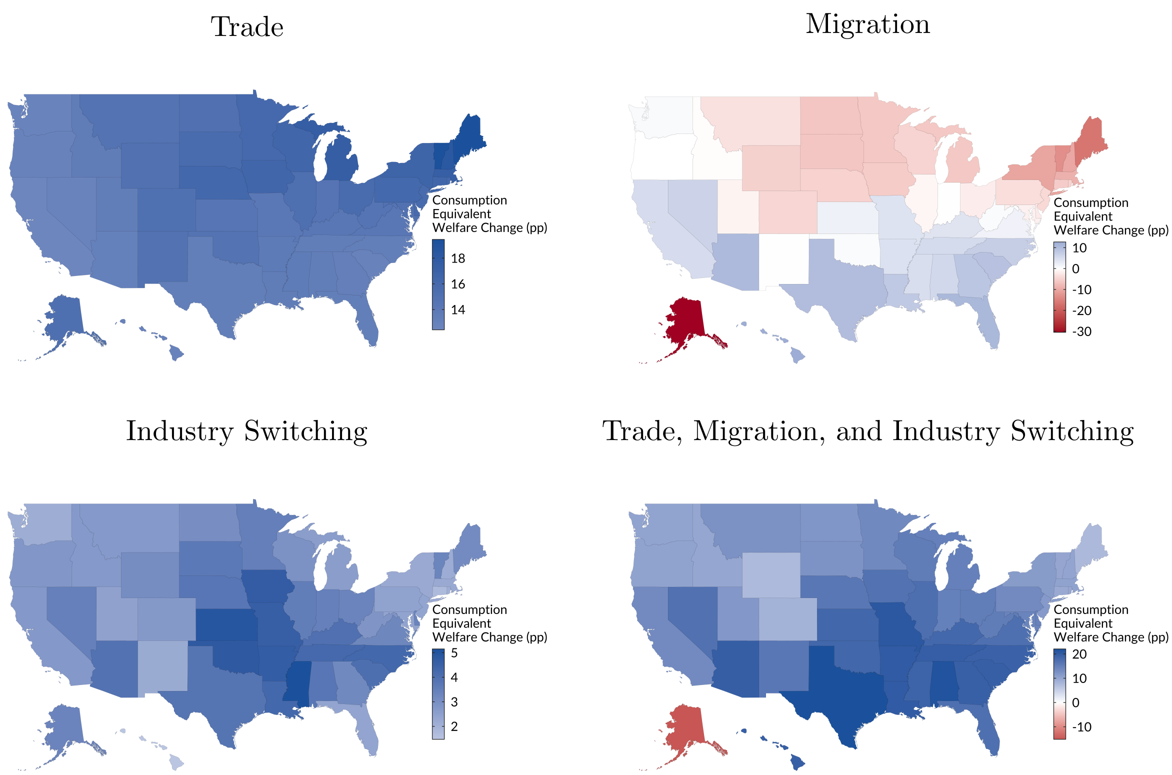
[25]The significant difference between the welfare impacts of migration and industry switching is partially due to the moving costs implied by the migration share data. Annually, only about 3% of households have an inter-state move, while 20% of workers switch industries. This suggests that migration incurs higher costs, dampening its welfare benefits.

Table 2: US welfare contribution of adaptation: 2015–2100.

Value of Trade Adjustments	Value of Migration	Value of Industry Switching	Value of Migration and Industry Switching	Value of Trade, Migration, and Industry Switching
12.9pp	1.1pp	3.1pp	3.9pp	13.7pp

Note:
Each column shows difference in welfare between our full model and a model without the listed adaptation mechanism.

Figure 9: Welfare value of adaptation mechanisms: climate shocks during 2015–2100.



Note: Each state is colored according to its state-specific Δ^A computed from comparing our full model relative to a model with one or more of the shares fixed. The top left panel holds trade shares fixed at their no climate change trajectories. The top right panel holds migration shares fixed at their no climate change trajectories. The bottom left panel holds industry switching shares fixed at their no climate change trajectories. The bottom right panel holds all three fixed at their no climate change trajectories. The welfare numbers for each state are computed identically to columns 1, 2, 3, and 5 in Table 2 and the population-weighted average across all states matches the values in the Table. The counterfactual scenario is if the annual temperature distribution for each location was held constant at its 2015 level for 2015–2100. Both the baseline and counterfactual are simulated for 2101–2200 with constant fundamentals ($\dot{Z}^k_{i,t} = 1$ for all i, k) to allow the full impacts of the shocks to unfold. All maps correspond to our full model with productivity shocks, amenity shocks, local structures, input-output loops, and heterogeneous response functions across industries.

Figure 9 shows the change in the US spatial distribution of welfare effects of adaptation, corresponding to Columns 1, 2, 3, and 5 of Table 2. The population-weighted average value across all states in the figure corresponds to the values reported in the table. The top left map shows the welfare value of trade adjustments. Trade makes all US states better off by substantial margins, with the largest gains in the Northeast and Midwest.

The top right map shows the welfare value of migration. Unlike trade, migration makes some states worse off. Alaska, Midwestern and Northeastern states are made worse off because households from other states migrate in and depress real wages for incumbent households. States outside the Midwest are better off because their households can move to the Midwest, Northeast, or Alaska which have higher productivity growth and better amenities under climate change relative to their origin state. Although some states are worse off with migration because of these pecuniary externalities, the average welfare effect is a small gain.

The bottom left map shows the welfare value of industry switching. Industry switching improves welfare in all states. The largest gains in welfare from industry switching are concentrated in the Central and Southern US, while the West and Northeast have the smallest gains.

The first three panels show that the three adaptation mechanisms all generate different spatial distributions of welfare impacts, and different levels of impacts. The bottom right panel shows the effect of all three mechanisms combined. Every state but Alaska is better off when able to adapt through trade in the labor market. Alaska is significantly worse off, with a welfare loss of about 15pp, because the negative effects of in-migration on incumbent households' real wages dominates any welfare gains from industry switching and trade adjustments. States in the South value adaptation the most and have welfare improvements of up to 20pp due to adaptation.

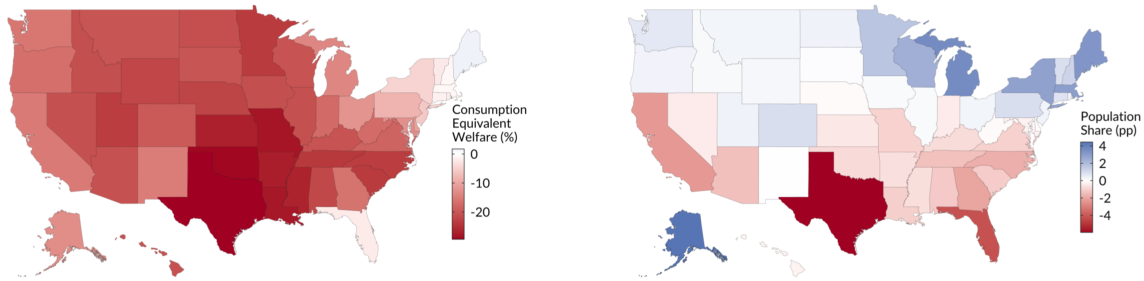
Table 2 and Figure 9 show that market adaptation has significant effects on the level and distribution of US welfare impacts of climate change. Market adaptation turns climate change from having large aggregate negative welfare effects to a small positive effect. Adaptation benefits every state but Alaska, and tends to heavily benefit states in the South where climate change will bring more extreme heat. Lower-income states in the south like Alabama and Mississippi value adaptation by up to 20% of consumption, suggesting that adaptation to climate change has progressive impacts on the US.

5.4 The Role of Economic and Climate Heterogeneity in Adaptation

Next we show the importance of industry and climatic heterogeneity for driving the value of adaptation. Market-based adaptation is valuable because it allows households to take advantage of heterogeneity in payoffs across locations or industries. Aggregating away heterogeneity may then understate the ability of households to adapt by arbitraging payoff differences across markets, and understate the benefits of adaptation.

Here we present difference-in-differences style results for how heterogeneity affects the value of adaptation. Let superscript $-H$ denote the welfare effect of climate change from a model with heterogeneity H omitted, superscript $-A$ denote the welfare effect of climate change from a model

Figure 10: US welfare and population effects with homogeneous climate impacts on industry-specific productivity growth: climate shocks during 2015–2100.



Note: The left panel shows the welfare impact as a percent of consumption averaged over the households in each state at the initial year. The right panes shows the change in population as a fraction of the total US population. The counterfactual scenario is if the annual temperature distribution for each location was held constant at its 2015 level for 2015–2100. Both the baseline and counterfactual are simulated for 2101–2200 with constant fundamentals ($\dot{Z}^k_{i,t} = 1$ for all i, k) to allow the full impacts of the shocks to unfold. Both maps correspond to our full model with productivity shocks, amenity shocks, local structures, and input-output loops.

with adaptation mechanism A omitted, and $-HA$ denote that when both are omitted. Our measure of the populated-weighted average welfare value of adaptation mechanism A under heterogeneity H versus without heterogeneity H is given by:

$$\Delta^{HA} := \underbrace{\left[\delta - \delta^{-A}\right]}_{\substack{\text{value of adaptation} \\ \text{with heterogeneity}}} - \underbrace{\left[\delta^{-H} - \delta^{-HA}\right]}_{\substack{\text{value of adaptation} \\ \text{without heterogeneity}}} .$$

This expression tells us how heterogeneity H amplifies the benefits of adaptation mechanism A. The more positive Δ^{HA} is, the more models abstracting from heterogeneity undervalue adaptation, while the more negative it is, the more they overvalue adaptation.

We focus on the three margins of heterogeneity presented in Section 5.2. First, we evaluate the importance of industry heterogeneity in productivity responses to temperature. Second, we evaluate the importance of intertemporal climatic heterogeneity: the heterogeneous evolution of within-year temperature variability across locations. Third, we evaluate the effects of spatial heterogeneity in the variability of temperature in addition to its spatial heterogeneity in changes over time by collapsing each location-year's daily temperature distribution down to its mean.

5.4.1 Industry Heterogeneity

We begin by showing that ignoring industry heterogeneity results in significantly different predictions for the distribution of welfare and population, i.e. that $\delta_n \neq \delta_n^{-H}$. Figure 10 replicates Figure 6 but where the model does not account for industry heterogeneity in productivity responses to temperature. Abstracting away from industry heterogeneity results in several differences. First, all states are projected to be worse off under climate change except for Maine. Migration patterns are similar to the simulation with heterogeneity, but net migration flows in and out of most

Table 3: US welfare contribution of adaptation due to heterogeneity: 2015–2100.

Attribute	Trade Adjustments	Migration	Industry Switching	Migration and Industry Switching	Trade, Migration, and Industry Switching
Industry Heterogeneity	10.3pp	-0.9pp	1.8pp	1.1pp	9.1pp
Time Variation in Daily Temperature Variability	-9.8pp	-1.5pp	-2.9pp	-4.4pp	-10.1pp
All Temperature Variability	-0.9pp	-0.5pp	-0.1pp	-0.1pp	-0.4pp

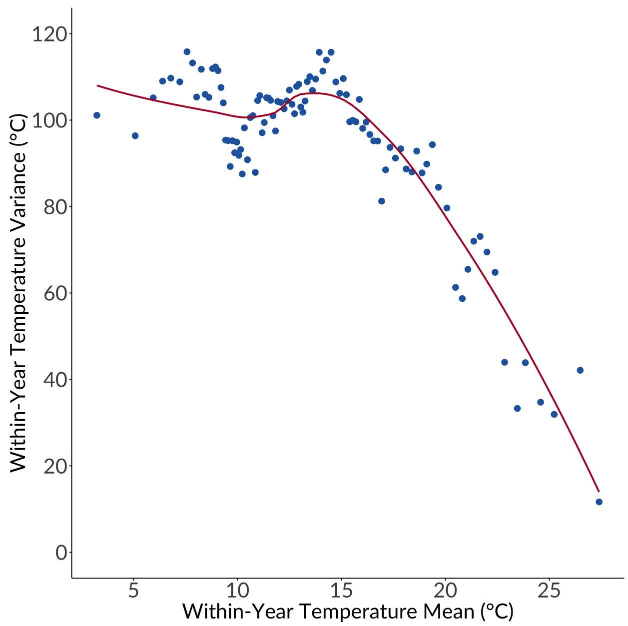
Note:
Each column shows the welfare value of each adaptation mechanism with the attribute in Column 1 versus without it.

states is larger in magnitude. Migration flows grow in magnitude because homogeneity in impacts across industries reduces the benefits of industry switching. Households treat migration and industry switching as substitutes, so reducing the benefits of industry switching amplifies cross-state migration flows.

The first row of Table 3 shows estimates of how industrial heterogeneity interacts with adaptation. Each column reports Δ^{HA}, the welfare value of adaptation attribute A with the listed heterogeneity H versus without. These entries tell us the importance of heterogeneity for adaptation, or alternatively, how much the value of each adaptation mechanism is underestimated in models that ignore heterogeneity.

The second column shows that the welfare benefits from trade shares endogenously adjusting to climate change increase by 10.3pp when accounting for industrial heterogeneity in climate impacts. This is almost all of the welfare benefit from trade reported in Table 2. The fourth column shows that the value of industry switching is amplified by 1.8pp because of heterogeneity, about half of the value of industry switching in Table 2. In essence, heterogeneity in industrial responses together with heterogeneous climate impacts effectively amplifies comparative advantage across locations thereby amplifying the benefits of trade and re-allocation across industries. The third column shows that migration adjustments to climate change are actually more valuable without industry heterogeneity. Without industrial heterogeneity, industry switching is less valuable which increases the relative benefits of migration. The combination of all three adaptation mechanisms has a 9.1pp larger impact because of industrial heterogeneity, which accounts for two-thirds of the total value market-based adaptation reported in Table 2.

Figure 11: The relationship between the mean and variance of within-year temperature at each location and year: 2015–2100.



Note: The mean and variance are computed for each location-year from 2015–2100. Each point plots the mean within-year temperature variance and mean within-year temperature mean for each percentile of the within-year temperature mean distribution. The red line is estimated using a local linear regression.

5.4.2 Temperature Variability Heterogeneity

The bottom two rows of Table 3 show the value of adaptation under temperature variability. The middle row shows results for changes in within-year variability across years, and the bottom row shows results for all temperature variability. The second column shows that trade is less valuable under the predicted changes in temperature variability over time. The benefits of trade as an adaptation mechanism decline by 9.8pp due to time variation in temperature variability, and by 0.9pp due to all within-year variability in temperature. Similarly, the benefits of migration and industry switching also decline due to temperature variability.

Why does within-year variability in temperature make market-based adaptation less valuable? One possibility is that temperature variability is negatively correlated with average temperature. If daily temperature variability is lower in hot regions relative to moderate regions, the positive welfare effect of lower variability — due to the concavity of the response functions — will tend to offset the negative welfare effect of hotter average temperatures. In this case, temperature variability tends to reduce welfare more in moderate regions compared to hot regions, thereby reducing heterogeneity in the overall impact on productivity and amenities and lowering the benefits of adaptation.

Figure 11 plots the variability of daily temperature against the mean of daily temperature for each location-year from 2015–2100 and shows that this story bears out in the data. The relationship is relatively flat until about an average daily temperature of 15°C, and then there is a clear negative relationship between average temperature and variability such that the hottest areas have one-fifth of the temperature variability of moderate regions. Warmer regions like Hawaii or Indonesia tend to have small temperature fluctuations throughout the year compared to cooler regions like Minnesota or France.[26]

This exercise raises two important points. First, although higher temperature variability decreases productivity growth and utility from amenities, higher variability also simultaneously dampens the heterogeneity in overall temperature impact across markets thereby depressing the benefits of adaptation. Intuitively, higher variability depresses absolute advantage across markets thereby magnifying welfare losses, but at the same time, higher variability compresses the differences in overall impact across markets and weakens comparative advantage. Comparative advantage is what matters for the value of adaptation. Second, introducing one dimension of heterogeneity might offset another dimension of heterogeneity captured in the model making the effect of introducing new forms of heterogeneity on comparative advantage across space and the value of adaptation unclear *a priori*.

6 Conclusion

In this paper we develop a dynamic-spatial general equilibrium trade model where climate change affects productivity growth and local amenities. Our approach allows us to tightly link our model to the data and simulate counterfactual outcomes without requiring information on the levels of non-temperature fundamentals such as migration costs, trade costs, or productivity. Our model and results have several implications for understanding and estimating the effects of climate change and the extent to which market forces – such as trade, industry switching and inter-state migration – can aid the economy in adapting to these changes.

First, our main quantitative result is that market adaptation is economically significant. We find that allowing trade patterns to adjust under climate change has large benefits to the US as a whole, and is the primary driver in mitigating the adverse effects of climate change. We find that industry switching is also vital and explains a third of the welfare gains from climate change, even after accounting for the presence of switching costs. Adaptation is most important for Southern states that are exposed to the greatest negative effects of climate change, with some states valuing the ability to adapt through market mechanisms at 20% of their consumption levels.

Second, we provide two new ways to estimate the effects of climate change on firm productivity growth and on household utility. Our model shows that in spatial equilibrium, income growth effects are well-identified by regressing growth in bilateral trade flows normalized by growth in a country's own expenditures on temperature, growth in trade costs, and growth in input prices. Data on time-varying trade costs like tariffs and input costs like wages are generally easy to obtain making

[26] Jakarta's daily maximum temperature throughout the year is almost always around 32°C, while in Minneapolis it can be as low as -6°C in the winter or as high as 28°C in the summer. Although Jakarta's hot temperatures worsen its growth and amenities relative to Minneapolis, Minneapolis' higher level of temperature variability reduces the difference in impacts between the two regions.

our approach an attractive alternative to standard approaches. Similarly, our model shows that we can estimate the effect of temperature on household utility, even when households are dynamically optimizing, given we have data on migration flows and wages to control for forward-looking behavior and effects on productivity and consumption of goods.

Our approach to estimating productivity effects circumvents hidden issues in empirical models that ignore spatial linkages. In addition to the extensive literature emphasizing the importance of dynamic behavior for identifying the effect of climate change, in Section B.3 in the Appendix we show that that spatial considerations also matter because the economy and climate are linked across space, which results in violations of standard identifying assumptions.

Overall, this paper shows the importance of heterogeneity, model structure, and market adaptation for quantifying the impacts of climate change. Important steps not taken in this paper may affect welfare and should be explored in future work. Our model focuses on labor-side mechanisms and ignores that firms behave dynamically and also invest in climate adaptation. Better accounting for firm-side adaptive responses would further increase any benefits and decrease any losses from climate change. We also abstract away from impacts on capital, and impacts of climate change that are not directly through temperature, such as sea level rise inundating coastal regions (Balboni, 2019; Desmet et al., 2021; Fried, 2021), or cyclone strikes (Bakkensen and Barrage, 2018). This will understate the costs of climate change as well as the benefits of migration and trade as adaptation mechanisms.

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Online Appendix

A Industry List and Map of Countries

Here we list the set of 20 industries by NAICS codes and give examples for what would fall into each.

NAICS 11: Agriculture, Forestry, Fishing, and Hunting
NAICS 21-22: Mining and Utilities
NAICS 23: Construction
NAICS 311-312: Food Manufacturing
NAICS 313-316: Textiles, Apparel, Leather Manufacturing
NAICS 321-323: Wood, Paper, and Printing
NAICS 324-327: Petroleum, Chemicals, Plastics, Minerals Manufacturing
NAICS 331-332: Primary Metal and Fabricated Metal Manufacturing
NAICS 333: Machinery Manufacturing
NAICS 334-335: Computers, Electronics, and Appliances Manufacturing
NAICS 336: Transportation Equipment Manufacturing
NAICS 337-339: Furniture and Miscellaneous Manufacturing
NAICS 42-45: Wholesale Trade and Retail Trade
NAICS 481-488: Transport Services
NAICS 511-512: Newspaper, Books, Software, Motion Pictures, and Music Production
NAICS 521-525: Finance and Insurance
NAICS 531-533: Real Estate
NAICS 61: Education
NAICS 721-722: Accommodation and Food Services
NAICS 493, 53, 541, 55, 562, 81: Other Services

B Details for Estimating Equations

Here we provide the details and derivations of our estimating equations, beginning with the construction of input costs for the estimation of temperature effects on productivity.

B.1 Input Cost Estimation

Recall that equation (9) gives us that:

$$x_{i,t}^k = \kappa_i^k \left(\left(r_{i,t}^k \right)^{\psi_k} \left(w_{i,t}^k \right)^{1-\psi_k} \right)^{\gamma_i^k} \prod_{s=1}^{K} \left(P_{i,t}^k \right)^{\gamma_i^{k,s}} .$$

We construct $x_{i,t}^k$ as follows. First, we observe wages and rental rates on capital and can insert those from the data. Second, we use the same values for all parameters as we use in the counterfactual simulations. The parameters are calibrated according to the description in Appendix D. Last, we must recover the $P_{i,t}^k$ terms. We do so by turning to another equilibrium condition of the model.

Begin by normalizing n's expenditures on goods from i by i's own expenditures:

$$\frac{X_{ni,t}^k}{X_{ii,t}^k} = \frac{X_{n,t}^k}{X_{i,t}^k} \left(\frac{P_{i,t}^k}{P_{n,t}^k} \tau_{ni,t}^k \right)^{-\theta^k} .$$

Move the ratio of total industry expenditures $X_{n,t}^k / X_{i,t}^k$ to the left hand side and then take the logarithm of both sides

$$\log \left(\frac{X_{ni,t}^k}{X_{n,t}^k} \right) - \log \left(\frac{X_{ii,t}^k}{X_{i,t}^k} \right) = -\theta^k \left[\log \left(P_{i,t}^k \right) - \log \left(P_{n,t}^k \right) + \log \left(\tau_{ni,t}^k \right) \right] . \tag{51}$$

The left hand side variable is the log difference in expenditure shares on imports from i to n relative to i's share at home, which is observed in the data. After pinning the coefficients to be equal to the trade elasticities calibrated in Appendix D, the log exporter price index term can be captured by a fixed effect $\eta_{i,t}^k$ and the log importer price index term can be captured by a fixed effect $\eta_{n,t}^k$. The trade cost term is just data. Exponentiating the fixed effect estimates gives us estimates of the price indices that we can use to construct the input cost variable for the regression in equation (17).

B.2 Derivation of Estimating Equation for Effects of Temperature on Utility

We now show how to derive the estimating equation for effects of temperature on utility. Recall that equation (19) gives us the option value of each market is less the migration costs to get to that market in the next period for a worker in market nk in the current period:

$$\bar{\epsilon}_{ni,t}^{ks} \equiv \frac{1}{\nu} \left[\beta \mathbb{E}_t \left(V_{i,t+1}^s - V_{n,t+1}^k \right) - \mu_{ni}^{ks} \right]$$

and is thus the value of $\epsilon_{n,t}^k - \epsilon_{i,t}^s$ (i.e. difference in idiosyncratic benefits) at which a worker in market nk is indifferent between staying in the same market and moving to market is. Rearranging this equation and substituting in the expected lifetime utilities from equation (18) yields the Euler equation:

$$\begin{aligned}
\nu\bar{\epsilon}^{ks}_{ni,t} + \mu^{ks}_{ni} &= \beta\mathbb{E}_t\left(V^s_{i,t+1} - V^k_{n,t+1}\right) \\
&= \beta\mathbb{E}_t\left[U(C^s_{i,t+1}, B_{i,t+1}) - U(C^k_{n,t+1}, B_{n,t+1}) + \mathbb{E}_{t+1}\left(V^s_{i,t+2} - V^k_{n,t+2}\right) + \Omega(\bar{\epsilon}^{\mathbf{s}}_{\mathbf{i,t+1}}) - \Omega(\bar{\epsilon}^{\mathbf{k}}_{\mathbf{n,t+1}})\right] \\
&= \beta\mathbb{E}_t\left[U(C^s_{i,t+1}, B_{i,t+1}) - U(C^k_{n,t+1}, B_{n,t+1}) + \nu\bar{\epsilon}^{ks}_{ni,t+1} + \mu^{ks}_{ni} + \Omega(\bar{\epsilon}^{\mathbf{s}}_{\mathbf{i,t+1}}) - \Omega(\bar{\epsilon}^{\mathbf{k}}_{\mathbf{n,t+1}})\right]
\end{aligned} \tag{52}$$

where:

$$\begin{aligned}
\Omega(\bar{\epsilon}^{\mathbf{k}}_{\mathbf{n,t}}) &\equiv \mathbb{E}_\epsilon\left[\max_{\{i,s\}^{N,K}_{i=1,s=0}}\left\{\nu\epsilon^s_{i,t} + \nu\bar{\epsilon}^{ks}_{ni,t}\right\}\right] \\
&= \sum_{i=1}^{N}\sum_{s=0}^{K}\int_{-\infty}^{\infty}\left(\nu\epsilon^s_{i,t} + \nu\bar{\epsilon}^{ks}_{ni,t}\right)\left(f\left(\epsilon^s_{i,t}\right)\prod_{lh\neq is}F\left(\epsilon^s_{i,t} + \bar{\epsilon}^{ks}_{ni,t} - \bar{\epsilon}^{kh}_{nl,t}\right)\right)d\epsilon^s_{i,t} \\
&= \nu\log\left(\sum_{i=1}^{N}\sum_{s=0}^{K}\exp\left[\left(\beta\mathbb{E}_t\left(V^s_{i,t+1} - V^k_{n,t+1}\right) - \mu^{ks}_{ni}\right)/\nu\right]\right).
\end{aligned}$$

Note that the last equality follows from Appendix A in Caliendo et al. (2019), hence we omit the detailed steps.

Like in Artuc et al. (2010), the Euler equation given by equation (52) tells us that for the marginal mover from market nk to is, the cost of moving including the idiosyncratic component (left hand side) is equal to the expected future benefit of being in market is instead of nk at time $t+1$ (right hand side). It also suggests that the trajectory of migration flows are sufficient statistics for the value functions in the future, and can thus be used to estimate the impact of climate change on amenities.

Specifically, we now show that the option value of moving markets $\Omega(\bar{\epsilon}^{\mathbf{k}}_{\mathbf{n,t}})$ and the difference in idiosyncratic benefits that leaves the marginal worker indifferent to moving $\bar{\epsilon}^{ks}_{ni,t}$ can be expressed as functions of only migration shares. Recall that the migration shares are given by equation (6):

$$\pi^{ks}_{ni,t} = \frac{\exp\left[\left(\beta\mathbb{E}_t\left(V^s_{i,t+1}\right) - \mu^{ks}_{ni}\right)/\nu\right]}{\sum_{l=1}^{N}\sum_{h=0}^{K}\exp\left[\left(\beta\mathbb{E}_t\left(V^h_{l,t+1}\right) - \mu^{kh}_{nl}\right)/\nu\right]}$$

Thus the share of workers who remained in the same market nk at time t is given by:

$$\pi^{kk}_{nn,t} = \frac{\exp\left[\left(\beta\mathbb{E}_t\left(V^k_{n,t+1}\right)\right)/\nu\right]}{\sum_{l=1}^{N}\sum_{h=0}^{K}\exp\left[\left(\beta\mathbb{E}_t\left(V^h_{l,t+1}\right) - \mu^{kh}_{nl}\right)/\nu\right]}.$$

Taking logs, we obtain:

$$\begin{aligned}
\log\pi^{kk}_{nn,t} &= \frac{1}{\nu}\beta\mathbb{E}_t\left(V^s_{i,t+1}\right) - \log\sum_{l=1}^{N}\sum_{h=o}^{K}\exp\left[\left(\beta\mathbb{E}_t\left(V^h_{l,t+1}\right) - \mu^{kh}_{nl}\right)/\nu\right] \\
\implies -\nu\log\pi^{kk}_{nn,t} &= \nu\log\left(\sum_{l=1}^{N}\sum_{h=0}^{K}\exp\left[\left(\beta\mathbb{E}_t\left(V^h_{l,t+1} - V^s_{i,t+1}\right) - \mu^{kh}_{nl}\right)/\nu\right]\right) \equiv \Omega(\bar{\epsilon}^{\mathbf{k}}_{\mathbf{n,t}}).
\end{aligned} \tag{53}$$

Taking logs of the ratio of migration shares against the share of workers who remain in the same market, the difference in idiosyncratic benefits $\bar{\epsilon}^{ks}_{ni,t}$ that leaves the marginal worker indifferent to moving can be expressed as:

$$\log\left(\frac{\pi^{ks}_{ni,t}}{\pi^{kk}_{nn,t}}\right) = \frac{\beta}{\nu}\mathbb{E}_t\left(V^s_{i,t+1} - V^k_{n,t+1}\right) - \frac{\mu^{ks}_{ni}}{\nu} \equiv \bar{\epsilon}^{ks}_{ni,t}. \tag{54}$$

Finally, we derive the critical conditional moment condition in the paper (equation (20)) by substituting the expressions for $\Omega(\bar{\epsilon}^{\mathbf{k}}_{\mathbf{n,t}})$ and $\bar{\epsilon}^{ks}_{ni,t}$, given by equations (53) and (54) respectively, into the Euler equation (equation (52)):

$$
\begin{aligned}
&\nu\bar{\epsilon}^{ks}_{ni,t} + \mu^{ks}_{ni} = \beta\mathbb{E}_t\left[U(C^s_{i,t+1}, B_{i,t+1}) - U(C^k_{n,t+1}, B_{n,t+1}) + \nu\bar{\epsilon}^{ks}_{ni,t+1} + \mu^{ks}_{ni} + \Omega(\bar{\epsilon}^{\mathbf{s}}_{\mathbf{i,t+1}}) - \Omega(\bar{\epsilon}^{\mathbf{k}}_{\mathbf{n,t+1}})\right] \\
\implies &\nu\log\left(\frac{\pi^{ks}_{ni,t}}{\pi^{kk}_{nn,t}}\right) + \mu^{ks}_{ni} = \beta\mathbb{E}_t\left[\log\left(\frac{B_{i,t+1}}{B_{n,t+1}}\frac{C^s_{i,t+1}}{C^k_{n,t+1}}\right) + \nu\log\left(\frac{\pi^{ks}_{ni,t+1}}{\pi^{kk}_{nn,t+1}}\right) + \mu^{ks}_{ni} + \nu\log\left(\frac{\pi^{kk}_{nn,t+1}}{\pi^{ss}_{ii,t+1}}\right)\right] \\
\implies &\mathbb{E}_t\left[\frac{\beta}{\nu}\log\left(\frac{B_{i,t+1}}{B_{n,t+1}}\frac{C^s_{i,t+1}}{C^k_{n,t+1}}\right) + \beta\log\left(\frac{\pi^{ks}_{ni,t+1}}{\pi^{ss}_{ii,t+1}}\right) - \log\left(\frac{\pi^{ks}_{ni,t}}{\pi^{kk}_{nn,t}}\right) + \frac{\beta-1}{\nu}\mu^{ks}_{ni}\right] = 0.
\end{aligned}
$$

B.3 Standard GDP Growth Approaches

Here we show how standard approaches regressing GDP or GDP growth on temperature are confounded by spatial linkages in the economy. Re-arranging equation (41), we can show that GDP growth can be written as:

$$
\log\left(\frac{Y^k_{n,t}}{Y^k_{n,t-1}}\right) = g(\mathbf{T}_{n,t};\zeta^k_{\mathbf{Z}}) + \log\left(1+\wp^k_{n,t}\right) - \theta^k\log\left(\frac{x^k_{n,t}}{x^k_{n,t-1}}\right) - \theta^k\log\left(\frac{\Lambda^k_{n,t}}{\Lambda^k_{n,t-1}}\right).
$$

GDP growth is a function of temperature, the base fundamental productivity growth rate, input costs, and firm market access. The important term here is growth in firm market access growth $\log\left(\frac{\Lambda^k_{n,t}}{\Lambda^k_{n,t-1}}\right)$ where:

$$
\Lambda^{-\theta^k}_{n,t} \equiv \sum_{i=1}^{N}\frac{(\tau_{in,t})^{-\theta^k}X_{i,t}}{\sum_{l=1}^{N}Z^k_{l,t}\left(x^k_{l,t}\tau^k_{il,t}\right)^{-\theta^k}}.
$$

Firm market access is a multilateral term that is a function of all countries' productivities, and thus all countries' temperature distributions. Temperature is positively spatially correlated, so firm market access $\Lambda^k_{n,t}$ is correlated with own temperature $\mathbf{T}_{n,t}$. Since most regressions omit time-varying firm market access, estimates of $\zeta^k_{\mathbf{Z}}$ will be biased since temperature will be correlated with the error term.

C Numerical Algorithms for Solving the Model

In this appendix we provide the numerical algorithms to solve the model that is consistent with the data and generate counterfactual trajectories, which build on CDP Propositions 1-3 described in the paper. The key takeaway of the propositions and algorithms is that we are able to simulate the baseline economy as well as solve for counterfactual changes without knowing the levels of the time-invariant exogenous fundamentals $\bar{\Theta} = \{b, \mu, H\}$ and time-varying exogenous fundamentals $\Theta_t = \{B_t, Z_t, \tau_t\}$. Note that $\dot{Y}_{t+1} \equiv \frac{Y_{t+1}}{Y_t}$ represents time changes, and $\widehat{Y}_t \equiv \frac{\dot{Y}_t'}{\dot{Y}_t}$ represents counterfactual time changes $\dot{Y}_t'$ relative to the baseline time changes $\dot{Y}_t$ for any variable Y.

C.1 Solving the model in time changes

Here we state how to solve the model in time changes numerically.

In particular, Proposition 1 shows us how to solve the momentary equilibrium at each t in time differences given the equilibrium in the previous period, which forms the inner loop of the numerical algorithm. The specific steps drawn from CDP are as follows:

- **Step 1**: For each $t \geq 0$, given $\dot{L}^k_{n,t+1}$ from the labor supply decision in the outer loop (described below), guess a value for $\dot{w}^{k(0)}_{n,t+1}$ where the superscript (0) indicates it is a guess.
- **Step 2**: Solve for prices $\dot{P}^k_{n,t+1}$ using equation (22) and (23) by looping over guesses for $\dot{P}^k_{n,t+1}$. Specifically, for each guess of $\dot{P}^k_{n,t+1}$, obtain $\dot{x}^k_{n,t+1}$ from equation (22) and check whether the value of $\dot{P}^k_{n,t+1}$ from equation (23) is close to the guess. Update the guess of $\dot{P}^k_{n,t+1}$ and repeat till a suitable pre-specified tolerance level is met.
- **Step 3**: Use equation (24) and $\dot{P}^k_{n,t+1}$ to obtain $\lambda^k_{ni,t+1}$.
- **Step 4**: Use equation (25), $\lambda^k_{ni,t+1}$, the current guess $\dot{w}^{k(0)}_{n,t+1}$, and $\dot{L}^k_{n,t+1}$ (given by the outer loop) to obtain $X^k_{n,t+1}$.
- **Step 5**: Use equation (26), $X^k_{n,t+1}$, and $\dot{L}^k_{n,t+1}$ (from the outer loop) to obtain a value for $\dot{w}^{k(1)}_{n,t+1}$. Check this value against the initial guess. If it is within a pre-specified tolerance level, the momentary equilibrium at time t is solved. Otherwise, update the guess for $\dot{w}^k_{n,t+1}$ and return to Step 1.
- **Step 6**: Repeat Steps 1-5 for every period t to obtain the trajectories for wages and prices $\{\dot{w}^k_{n,t+1}, \dot{P}^k_{n,t+1}\}^T_{t=0}$ i.e. solve the momentary equilibrium for all t.

Given how to solve the momentary equilibrium or production side of the economy at each t in time differences, we then use Proposition 2 to solve for the outer loop of the economy numerically (changes to CDP algorithm in bold):

- **Step 1**: Guess a path of $\{\dot{u}^{k(0)}_{n,t+1}\}^T_{t=0}$ that converges to $\dot{u}^{k(0)}_{n,T+1} = 1$. **Note that this guess includes the exogenous climate damage and amenity change components**.
- **Step 2**: For all $t \geq 0$, use the guess $\{\dot{u}^{k(0)}_{n,t+1}\}^T_{t=0}$ and the initial migration shares across markets $\pi^{ks}_{ni,-1}$ to solve for the trajectory of migration shares $\{\pi^{ks}_{ni,t}\}^T_{t=0}$ [using equation (27)].
- **Step 3**: Use the trajectory of $\{\pi^{ks}_{ni,t}\}^T_{t=0}$ and the initial labor allocation/supply across sectors $L^k_{n,0}$ to solve for the trajectory of labor allocations/supply $\{L^k_{n,t}\}^T_{t=0}$ [using equation (29)].

- **Step 4**: Use the trajectory of labor allocations in Step 3 to solve the production side for each period (see algorithm for the inner loop above). This yields the trajectories for wages and prices $\{\dot{w}^k_{n,t+1}, \dot{P}^k_{n,t+1}\}^T_{t=0}$. From $\{\dot{w}^k_{n,t+1}, \dot{P}^k_{n,t+1}\}^T_{t=0}$ we have the trajectory of real wages $\{\dot{\omega}^k_{n,t+1}\}^T_{t=0}$.
- **Step 5**: For each time t, use $\dot{u}^{k(0)}_{n,t+2}$ from the initial guess [Step 1], the migration shares $\{\pi^{ks}_{ni,t}\}^T_{t=0}$ from Step 2, the real wages $\dot{\omega}^k_{n,t+1}$ from Step 4, and **the exogenous *time* changes in amenities** $\dot{B}_{n,t+1}$ to solve for $\dot{u}^{k(1)}_{n,t+1}$ [using equation (28)]. This yields a new path of $\{\dot{u}^{k(1)}_{n,t+1}\}^T_{t=0}$.
- **Step 6**: If $\{\dot{u}^{k(0)}_{n,t+1}\}^T_{t=0} \approx \{\dot{u}^{k(1)}_{n,t+1}\}^T_{t=0}$ i.e. the maximum difference across all t is less than some pre-specified tolerance level, $\{\dot{u}^{k(0)}_{n,t+1}, \pi^{ks}_{ni,t}, L^k_{n,t}\}^T_{t=0}$ is the solution to the problem. Otherwise update the initial guess to be $\{\dot{u}^{k(1)}_{n,t+1}\}^T_{t=0}$ and repeat the steps until convergence.

Combining the algorithms for the inner and outer loops, we can solve for the sequential competitive equilibrium numerically given an initial allocation of the economy and an anticipated convergence sequence of time changes in fundamentals.

C.2 Solving the model for counterfactual outcomes

Just as Propositions 1 and 2 allow us to develop a numerical algorithm to solve for the baseline economy given an initial allocation of the economy and an anticipated convergent sequence of time changes in fundamentals, so Proposition 3 provides us with the equations in counterfactual changes to develop a numerical algorithm to solve for the counterfactual economy given the baseline economy and an anticipated convergent sequence of counterfactual changes. Specifically, the algorithm mirrors that to solve the baseline economy above, and is given as follows (changes to CDP algorithm in bold):

- **Step 1**: Guess a path of $\{\widehat{u}^{k(0)}_{n,t+1}\}^T_{t=0}$ that converges to $\widehat{u}^{k(0)}_{n,T+1} = 1$. **Note that this guess includes the exogenous climate damage component**.
- **Step 2**: For all $t \geq 0$, use the guess $\{\widehat{u}^{k(0)}_{n,t+1}\}^T_{t=0}$, the initial migration shares across sectors $\pi^{ks}_{ni,-1}$, and the time changes in migration shares in the baseline economy $\{\dot{\pi}_{t-1}\}^T_{t=0}$ to solve for the trajectory of migration shares $\{\pi^{ks}_{ni,t}{}'\}^T_{t=0}$ [using equation (30)]
- **Step 3**: Use the trajectory of $\{\pi^{ks}_{ni,t}{}'\}^T_{t=0}$ and the initial labor allocation/supply across sectors $L^k_{n,0}$ to solve for the trajectory of labor allocations/supply $\{L^k_{n,t+1}{}'\}^T_{t=0}$ [using equation (32)]
- **Step 4**: Use the trajectory of labor allocations in Step 3 to solve the production side for each period:
  - (a) For each $t \geq 0$, given $\widehat{L}^k_{n,t+1}$ computed from Step 3, guess a value for $\widehat{w}^{k(0)}_{n,t+1}$.
  - (b) Solve for prices $\widehat{P}^k_{n,t+1}$ using equations (33) and (34) by looping over guesses for $\widehat{P}^k_{n,t+1}$. Specifically, for each guess of $\widehat{P}^k_{n,t+1}$, obtain $\widehat{x}^k_{n,t+1}$ from equation (33) and check whether the value of $\widehat{P}^k_{n,t+1}$ from equation (34) is close to the guess. Update the guess of $\widehat{P}^k_{n,t+1}$ and repeat till a suitable pre-specified tolerance level is met.
  - (c) Use equation (35) and $\widehat{P}^k_{n,t+1}$ to obtain $\widehat{\lambda}^k_{ni,t+1}$.
  - (d) Use equation (36), $\widehat{\lambda}^k_{ni,t+1}$, the current guess $\widehat{w}^k_{n,t+1}$, $\widehat{L}^k_{n,t+1}$ (computed from Step 3), and the baseline $\dot{\lambda}^k_{ni,t+1}$ to obtain $X^k_{n,t+1}{}'$.
  - (e) Use equation (37), $X^k_{n,t+1}{}'$, and $\widehat{L}^k_{n,t+1}$ (computed from Step 3) to obtain a (new) value for $\widehat{w}^{k(1)}_{n,t+1}$. Check this value against the initial guess. If it is within a pre-specified tolerance level, the momentary equilibrium at time t is solved. Otherwise, update the guess for $\widehat{w}^k_{n,t+1}$ and return to Step 4(a).

(f) Repeat Steps 4(a)-(e) for every period t to obtain the trajectories for wages and prices $\{\widehat{w}^k_{n,t+1}, \widehat{P}^k_{n,t+1}\}^T_{t=0}$ i.e. solve the momentary equilibrium for all t. From $\{\widehat{w}^k_{n,t+1}, \widehat{P}^k_{n,t+1}\}^T_{t=0}$ we have the trajectory of real wages $\{\widehat{\omega}^k_{n,t+1}\}^T_{t=0}$.

- **Step 5**: For each time t, use $\widehat{u}^{k(0)}_{n,t+2}$ from the initial guess [Step 1], the migration shares $\{\pi^{ks}_{ni,t}{}'\}^T_{t=0}$ from Step 2, the real wages $\widehat{\omega}^k_{n,t+1}$ from Step 4, and **the exogenous *counterfactual* changes in amenities** $\widehat{B}_{n,t}$ to solve for $\widehat{u}^{k(1)}_{n,t+1}$ [using equation (31)]. This yields a new path of $\{\widehat{u}^{k(1)}_{n,t+1}\}^T_{t=0}$.
- **Step 6**: If $\{\widehat{u}^{k(0)}_{n,t+1}\}^T_{t=0} \approx \{\widehat{u}^{k(1)}_{n,t+1}\}^T_{t=0}$ i.e. the maximum difference across all t is less than some pre-specified value, $\{\widehat{u}^{k(0)}_{n,t+1}, \pi^{ks}_{ni,t}{}', L^k_{n,t}{}'\}^T_{t=0}$ is the solution to the problem. Otherwise update the initial guess to be $\{\widehat{u}^{k(1)}_{n,t+1}\}^T_{t=0}$ and repeat the steps until convergence.

C.3 Utilizing data for the historical simulations

A core feature of this model is that migration flows are sufficient statistics for migration costs on the household side, and total expenditures and trade shares are sufficient statistics for trade costs and productivities on the production side. To utilize data for the historical simulations, we follow Caliendo et al. (2019) and use the algorithm for solving counterfactual outcomes above for the production side. Note that we are exploiting the fact that **the relative change in fundamentals between our model and the data is 1**. In particular, we use data on bilateral expenditures and trade shares $\{X_t, \lambda_t\}^\infty_{t=0}$ as the baseline economy, and compute the model-implied trajectories of these variables $\{X'_t, \lambda'_t\}^\infty_{t=0}$. Mechanically, we sum over bilateral expenditures in the data to attain total value added in each market, and compute the implied unit cost less intermediate inputs to feed into equation (33). We also feed in data on trade shares in equation (30) and compute the model-implied trajectories as outlined in Step 4 of the algorithm for solving counterfactual outcomes above. For the household side, we do not update the outer loop (Steps 1-3, 5-6 in the algorithm above) and instead use the time series data on migration flows to fix the trajectory of labor allocations. The simulated trajectory of migration shares, labor allocations, trade shares and total expenditures thus form our baseline economy in the past, where the simulated migration shares exactly match those observed in the data, whereas the trade expenditures and shares do not. We can then use the full algorithm to solve for counterfactual outcomes against this historical baseline economy, given a counterfactual change in fundamentals.

D Data for Simulations

Data for the counterfactual come from the following sources: the World Input Output Database (WIOD), the Bureau of Economic Analysis (BEA), The Organization for Economic Cooperation and Development (OECD), the 2012 U.S. Commodity Flow Survey, the 2012 American Community Survey, and the U.S. 2012 Current Population Survey. Here we describe how we calibrate model parameters and construct time series of variables along with the data sources for each. Much of the calibration follows from CDP.

D.1 Labor Share of Value Added

Non-US Countries The WIOD reports value added for each industry-country-year. We combine this with data from the OECD on labor compensation as a fraction of value added. The OECD data are not reported for all countries so we impute for the missing values with the median of the observed countries.

States We use data from the BEA to compute value added as GDP net of taxes and subsidies, as well as total labor compensation for each industry-state. The labor share of value added is the ratio of these two values.

D.2 Bilateral Trade Flows

Across Countries Bilateral trade flows across countries comes from the WIOD.

Across US States Bilateral trade flows across states comes from the 2012 CFS. We use these cross-state bilateral trade flows to construct expenditure shares for each industry. For industries not in the CFS, we impute expenditure shares as the state-level expenditure share across all observed industries. We then multiply each state's industry expenditure share by the US total industry domestic expenditures in the WIOD to recover cross-state bilateral trade flows that match the level of total US domestic expenditures in the WIOD data.

Between US States and Other Countries First, we use the BEA data on industry employment to construct state employment shares for each industry. We then assign each state's bilateral expenditures with non-US countries to be the product of the employment share in the industry and the US total bilateral expenditures in the industry.

D.3 Value Added Share of Gross Output

We construct gross output for each country and state using the previously constructed bilateral expenditures. We obtain value added as described above. The share of value added in gross output in the ratio of these two values. For industries not in the CFS, we do not have gross output so we impute their value added share to be the median of the observed industries.

D.4 Intermediates Share of Gross Output

We construct the share of each industry using expenditures on intermediates in the WIOD. We then scale these values using the value added share of gross output so that the sum of the value added share and all intermediates shares is equal to 1.

D.5 Consumption Shares

We construct consumption shares, common across all states and countries, using the WIOD as the ratio of industry spending to total spending.

D.6 Local Capitalist Share of the Global Portfolio

We construct local capitalist shares identically to CDP. We use year 2000 WIOD data to construct the trade imbalance at each location, TI_n. We combine this with our estimates of value added and the share of local structures in value added to get the local capitalist shares:

$$\iota_n = \frac{\sum_{k=1}^{K} \psi^k VA_n^k - TI_n}{\sum_{n=1}^{N} \sum_{k=1}^{K} \psi^k VA_n^k}.$$

D.7 Labor and Structure Value Added

We get value added for labor and structures using the structure share of value added in conjunction with the value added estimates described above.

D.8 Initial Distribution of Labor

We use the 2000 Census to construct the initial distribution of labor. We include individuals between 25 and 65.[27]

D.9 Migration Shares

We use annual data on migration across states from the Public Use Micro Sample (PUMS) of the American Community Survey (ACS) 2000-2014, and monthly data on migration across sectors using Current Population Survey (CPS) 2000-2014 to construct an annual transition matrix across markets following the method in CDP.

[27] Vermont has one industry with no reported employment in the ACS so we insert a value of 1 rather than omit it entirely.

E Details for Simulations

To produce our counterfactual outcomes for the future simulations we use temperature projections from the Coupled Model Intercomparison Project (CMIP6), that correspond to specific Shared Socioeconomic Pathways (SSPs) and Representative Concentration Pathways (RCPs). Specifically, we use the SSP2-4.5 scenario. This scenario corresponds to RCP4.5 which yields radiative forcing of 4.5 W/m^2 at the end of the century. RCP4.5 is often considered an intermediate, high probability scenario. End of century global average warming is approximately 2.5°C along this scenario. The change in temperature variance under this scenario is presented in Figure A6.

We construct the relative changes in fundamental productivity growth for the historical and forward simulations as follows.

E.1 Historical Simulation

E.1.1 Baseline

For the historical baseline economy, we simulate the economy with time-varying fundamentals from 2000–2014 since we observe the sufficient statistics – trade flows, migration flows, and expenditures – over that time period. After 2014, we simulate the economy forward until 2115 with constant fundamentals and no shocks to productivity or amenities so that:

$$\dot{Z}^k_{i,t} = \dot{B}^k_{i,t} = 1 \quad \forall t \geq 2015.$$

E.1.2 Counterfactual

For the historical counterfactual economy we simulate the economy with time-varying fundamentals, but where the temperature distribution from 2000–2014 is held constant at 2000 levels. We do this by first inverting the actual temperature impacts on productivity and amenities in the model, and then assigning the year 2000 temperature impacts. The counterfactual change in productivity $\widehat{Z}^k_{n,t}$ is then:

$$\widehat{Z}^k_{n,t} = \frac{\dot{Z}^{k\,'}_{i,t}}{\dot{Z}^k_{i,t}} = \frac{\left(1 + r^{k\,'}_{i,t}\right)\exp(g(\boldsymbol{T}^{'}_{i,t};\zeta_{\mathbf{Z}}))}{\left(1 + r^k_{i,t}\right)\exp(g(\boldsymbol{T}_{i,t};\zeta_{\mathbf{Z}}))} = \exp(g(\boldsymbol{T}^{'}_{i,t};\zeta_{\mathbf{Z}}) - g(\boldsymbol{T}_{i,t};\zeta_{\mathbf{Z}})).$$

The base growth rates cancel out since they are not changing from the baseline to the counterfactual. The counterfactual change in amenities $\widehat{B}_{n,t}$ at each time t is then given by:

$$\begin{aligned}\widehat{B}_{n,t} &= \frac{\dot{\overline{B}}'_{n,t}}{\dot{\overline{B}}_{n,t}} \frac{\exp\left(f(\mathbf{T}'_{n,t};\zeta_{\mathbf{B}}) - f(\mathbf{T}'_{n,t-1};\zeta_{\mathbf{B}})\right)}{\exp\left(f(\mathbf{T}_{n,t};\zeta_{\mathbf{B}}) - f(\mathbf{T}_{n,t-1};\zeta_{\mathbf{B}})\right)} \\ &= \exp\left[\left(f(\mathbf{T}'_{n,t};\zeta_{\mathbf{B}}) - f(\mathbf{T}'_{n,t-1};\zeta_{\mathbf{B}})\right) - \left(f(\mathbf{T}_{n,t};\zeta_{\mathbf{B}}) - f(\mathbf{T}_{n,t-1};\zeta_{\mathbf{B}})\right)\right]\end{aligned}$$

As with productivity, the base amenities cancel out since we assume they are not changing differently across the baseline and counterfactual. As in the baseline, we simulate the counterfactual forward from 2015 to 2115 with constant fundamentals and no relative shocks to productivity or amenities:

$$\widehat{Z}^{k\,'}_{i,t} = \widehat{B}^{k\,'}_{i,t} = 1 \quad \forall t \geq 2015.$$

The simultaneous simulations with constant fundamentals and no shocks from 2015–2115 allows the shocks from 2000–2014 to fully unfold, so we can compute the present value of the total effect of the shocks, rather than just the present value of their contemporaneous effect during 2000–2014.

E.2 Forward Simulation

For the forward simulation, we start in 2015, the first year after our historical simulation. Since we do not have all the required data to do the simulation allowing for unobserved time-varying fundamentals, we must simulate forward assuming constant fundamentals, except for the impact of temperature on productivity growth and amenities.

E.2.1 Baseline

For the baseline, we require the change in fundamental productivity $\dot{Z}^k_{i,t}$ which is composed of two parts:

$$\dot{Z}^k_{i,t} = \frac{Z^k_{i,t}}{Z^k_{i,t-1}} = \left(1 + r^k_{i,t}\right) \exp(g(\boldsymbol{T}_{i,t}; \zeta_{\mathbf{Z}})).$$

The first part is the base growth rate $\left(1 + r^k_{i,t}\right)$ which we set equal to 1 to focus on the impacts of temperature, as captured by the second part. We also require the change in amenities which we construct in a similar fashion:

$$\dot{B}_{n,t} = \dot{\overline{B}}_{n,t} \exp\left[\left(f(\boldsymbol{T}_{i,t}; \zeta_{\mathbf{B}}) - f(\boldsymbol{T}_{i,t-1}; \zeta_{\mathbf{B}})\right)\right].$$

We further assume that $\dot{\overline{B}}_{n,t} = 1$ so changes in amenities are solely given by the effect of temperature.

For the baseline temperature trajectories we assume that country-specific within-year daily temperature distributions follow our chosen climate scenario. We then extend the simulations to 2200 assuming $\dot{Z}^k_{i,t} = \dot{B}^k_{i,t} = 1$ after year 2100, similar to the historical simulations.

E.2.2 Counterfactual

For the counterfactual, we require the change in counterfactual fundamental productivity:

$$\dot{Z}^{k\ \prime}_{i,t} = \frac{Z^{k\ \prime}_{i,t}}{Z^{k\ \prime}_{i,t-1}} = \left(1 + r^{k\ \prime}_{i,t}\right) \exp(g(\boldsymbol{T}^{'}_{i,t}; \zeta_{\mathbf{Z}})),$$

and the change in counterfactual amenities:

$$\dot{B}^{'}_{n,t} = \dot{\overline{B}}^{'}_{n,t} \exp\left[\left(f(\boldsymbol{T}^{'}_{i,t}; \zeta_{\mathbf{B}}) - f(\boldsymbol{T}^{'}_{i,t-1}; \zeta_{\mathbf{B}})\right)\right].$$

For the counterfactual, we assume that $\left(1 + r^{k\ \prime}_{i,t}\right) = \dot{\overline{B}}^{'}_{n,t} = 1$ as in the baseline so that non-temperature components of productivity growth and amenities are constant. We then hold the within-year daily temperature distribution in each year constant at 2000 levels until 2100. After 2100 we set $\dot{Z}^{k\ \prime}_{i,t} = \dot{B}^{k\ \prime}_{i,t} = 1$ so there is no change in fundamentals relative to the baseline, again similar to the historical simulations. Thus, our results can be interpreted as the effect of changes in temperature given the SSP2-4.5 scenario, relative to maintaining the year 2000 observed temperature distribution.

E.3 Identifying Adaptation Channels

We are particular interested in quantifying the role of each adaptation channel on equilibrium outcomes from climate change. Here we build on the Propositions 4 and 5 in the paper and detail the numerical algorithms for our quantification exercises step-by-step.

E.3.1 Trade Adaptation

Given Proposition 4, our procedure for identifying the role of trade adaptation in the forward simulations is as follows:

- Step 1: Run the full baseline algorithm with climate change to get the full baseline economy with climate change
- Step 2: Run the full baseline algorithm to get the full counterfactual trajectories without climate change
- Step 3: Save the trajectory of trade shares
- Step 4: Run the baseline algorithm but with trade shares fixed to the ones from Step 2 (using the first part of Proposition 4) to obtain the baseline economy with climate change but without trade adaptation
- Step 5: Compare the results from Step 1 and 4 to attain the role of trade adaptation

Note that while we focus on climate change, these procedures can be used to identify the role of trade adaptation in response to *any* exogenous time or counterfactual changes in fundamentals, be it productivity, trade costs, migration costs or amenities.

E.3.2 Migration Adaptation

Given Proposition 5, our procedure for identifying the role of migration adaptation (both migration across regions and industry switching) in the forward simulations is as follows:

- Step 1: Run the full baseline algorithm with climate change to get the full baseline economy with climate change
- Step 2: Run the full baseline algorithm to get the full counterfactual trajectories without climate change
- Step 3: Save the trajectory of migration shares
- Step 4: Run the baseline algorithm but with migration shares fixed to the ones from Step 2 (using the first part of Proposition 5) to obtain the baseline economy with climate change but without migration adaptation
- Step 5: Compare the results from Step 1 and 4 to attain the role of migration adaptation

To tease out adaptation in migration across regions versus industry switching, we adopt a similar algorithm but alternative hold only industry switching fixed at average levels across all regions, and only migration across regions fixed at average levels across all industries.

F Derivation of Welfare Decomposition

We omit the proof for the first level of the welfare decomposition, as seen in equation (40) given its similarity to CDP. Here we show how to attain our decomposition of changes in wages and prices in equations (41)-(42). From the labor market clearing condition (equation 15), we have that:

$$w_{n,t}^k L_{n,t}^k = \gamma_n^k \left(1-\psi^k\right) Y_{n,t}^k$$

where $Y_{n,t}^k \equiv \sum_{i=1}^N \lambda_{in,t} X_{i,t} = \sum_{i=1}^N X_{in,t}$. Expressing this condition in terms of counterfactual changes, we obtain:

$$\widehat{w}_{n,t}^k = \frac{\widehat{Y}_{n,t}^k}{\widehat{L}_{n,t}^k}.$$

Now note that from the expression for trade shares from equation (12) we have:

$$Y_{n,t}^k = \sum_{i=1}^N \lambda_{in,t} X_{i,t} = \sum_{i=1}^N \frac{Z_{n,t}^k \left(x_{n,t}^k \tau_{in,t}^k\right)^{-\theta^k} X_{i,t}}{\sum_l Z_{l,t}^k \left(x_{l,t}^k \tau_{il,t}^k\right)^{-\theta^k}} = Z_{n,t}^k \left(x_{n,t}^k\right)^{-\theta^k} \sum_{i=1}^N \frac{\left(\tau_{in,t}^k\right)^{-\theta^k} X_{i,t}}{\sum_l Z_{l,t}^k \left(x_{l,t}^k \tau_{il,t}^k\right)^{-\theta^k}}.$$

Defining $\Lambda_{n,t}^{-\theta^k} \equiv \sum_{i=1}^N \frac{(\tau_{in,t})^{-\theta^k} X_{i,t}}{\Phi_{i,t}^k}$ where $\Phi_{i,t}^k \equiv \sum_{l=1}^N Z_{l,t}^k \left(x_{l,t}^k \tau_{il,t}^k\right)^{-\theta^k}$, we thus have that:

$$\log \widehat{w}_{n,t}^k = \log \widehat{Y}_{n,t}^k - \log \widehat{L}_{n,t}^k = \log \widehat{Z_{n,t}^k} - \theta^k \log \widehat{x_{i,t}^k} - \theta^k \log \widehat{\Lambda_n} - \log \widehat{L_{n,t}},$$

which is equation (41) in the paper.

The decomposition for prices is straightforward. Expressing the price aggregator in each region, given by equation (3), in counterfactual changes, we have:

$$\log \widehat{P_{n,t}} = \log \left(\prod_{s=1}^K \left(\widehat{P_{n,t}^s}\right)^{\alpha^s} \right) = \sum_{s=1}^K \alpha^s \log \widehat{P_{n,t}^s}.$$

Expressing the price index for each market from equation (13) in counterfactual changes and using the definition of $\Phi_{n,t}^s$, we have:

$$\widehat{P_{n,t}^s} = \left(\widehat{\Phi_{n,t}^s}\right)^{-1/\theta^s}.$$

Combining both equations above yields:

$$\log \widehat{P_{n,t}} = -\sum_{s=1}^K \frac{\alpha^s}{\theta^s} \log \widehat{\Phi_{n,t}^s},$$

which is equation (42) in the paper.

G Additional Results

This section contains additional results and robustness checks. Figure A2 plots our industry-specific damage functions by 2 or 3 digit NAICS codes. There is significant heterogeneity across industries in the shape and level of the curves.

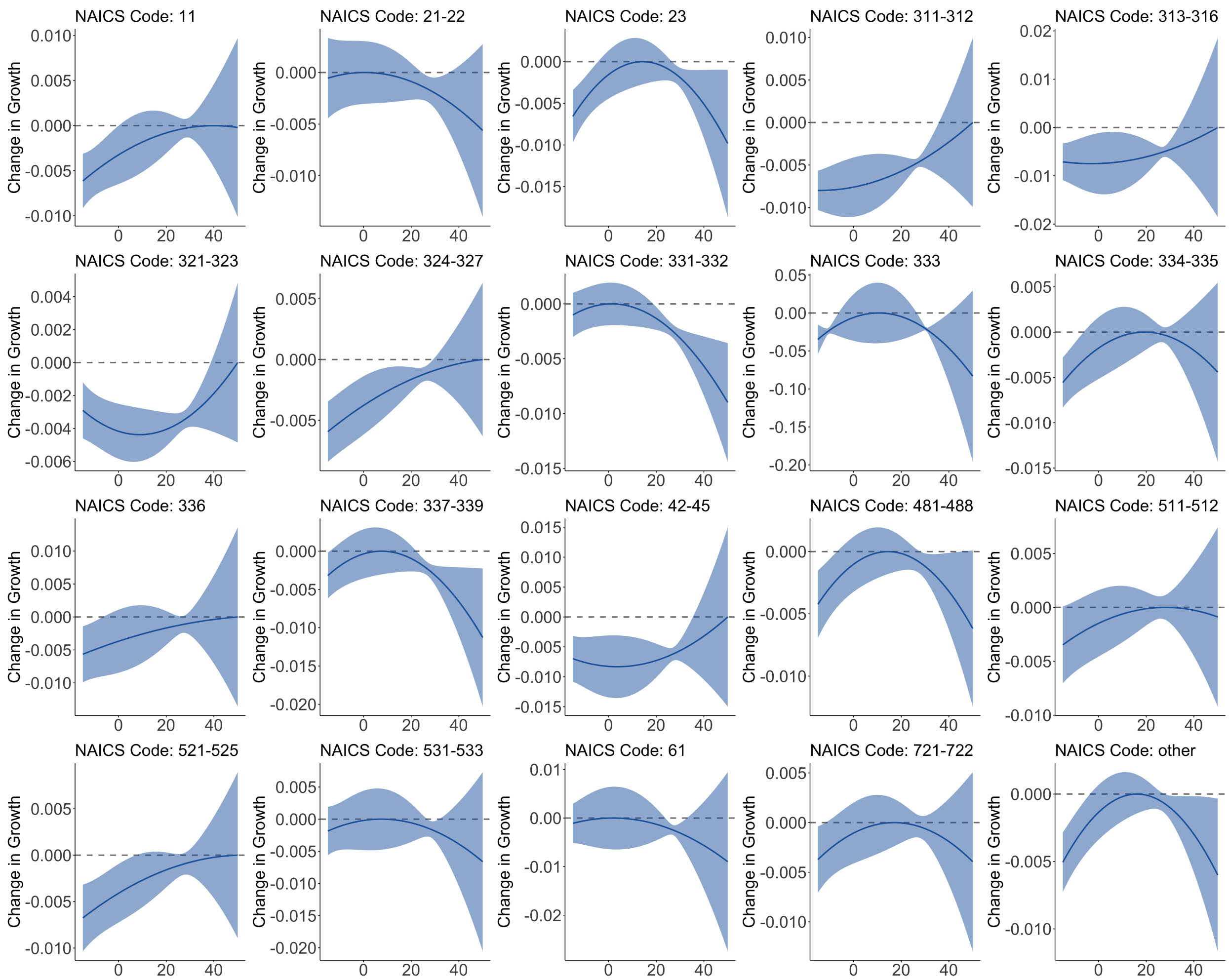
Figure A3 shows welfare results for the future simulation from a version of our model similar to implicit assumptions used when simulating climate impacts forward with country-level aggregate response functions. The model has no amenities, a common response function across all industries, no input-output loops, and no adaptation through trade or the labor market. Unlike our main results in Figure 6, welfare declines everywhere but Alaska with losses concentrated in the South.

Figure A4 plots the direct welfare effect of amenities (e.g. $\log\left(\widehat{B}_{i,t}\right)$), ignoring any indirect effects on real wages. Climate impacts on amenities are worst in the central US, and best in Florida and the Northeast.

Figure A5 plots several different estimates of our response functions. The left panels show the productivity growth response functions, and the right panels show the amenities response functions. The top row shows estimates using orthogonal polynomials of degrees 2–6, with our main specification in red. The bottom show estimates using cubic splines with 1–5 evenly spaced knots. In general, all the response functions are similar except the higher order response functions, particularly for amenities, tend to be overfit and wavy.

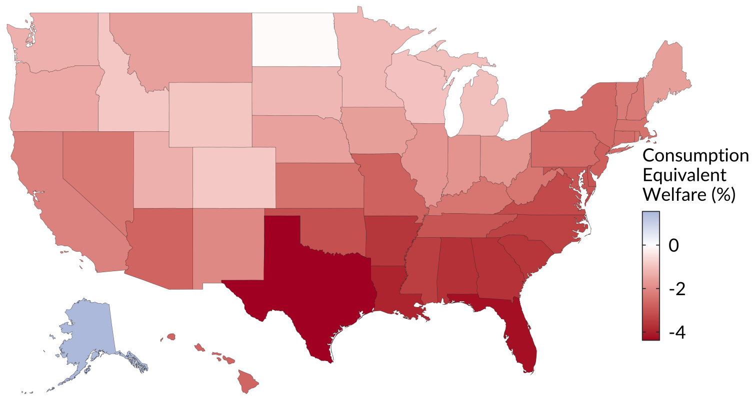
Figure A6 shows a stacked bar chart of the distribution of the change in average temperature variance for each location from 2015–2024 to 2091–2100. The majority of countries and states are predicted to have an increase in temperature variability by the end of the century.

Figure A2: The direct effect of temperature on productivity by industry.



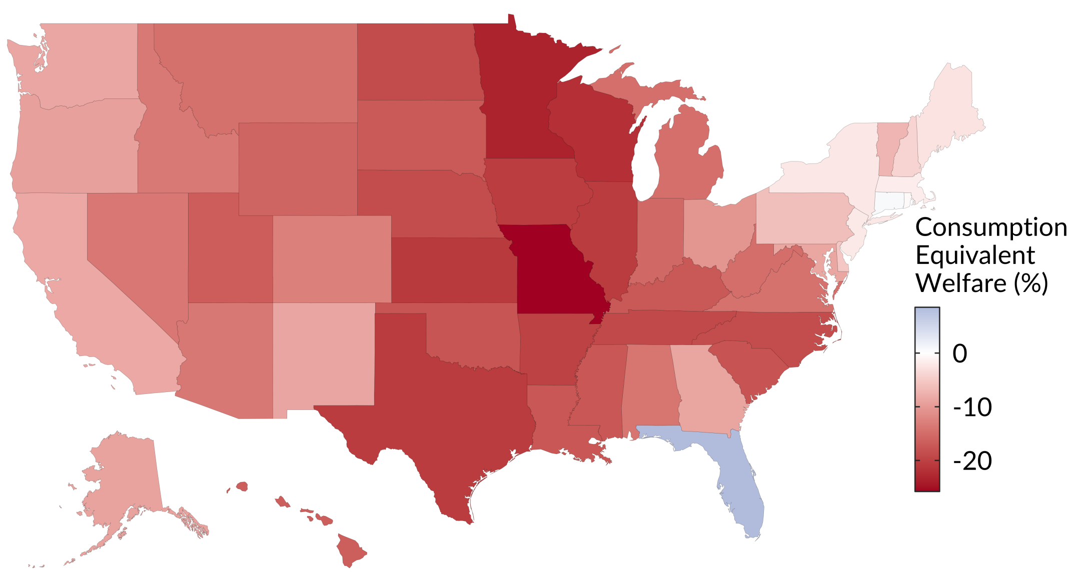
Note: The response functions are constructed using a second degree orthogonal polynomial approximation to the distribution of intra-annual daily temperatures. The shaded areas denote the 95% confidence intervals. The response function is from estimating equation (17) but where g is interacted with a set of industry dummy variables.

Figure A3: US welfare effects under standard assumptions: climate shocks during 2015–2100.



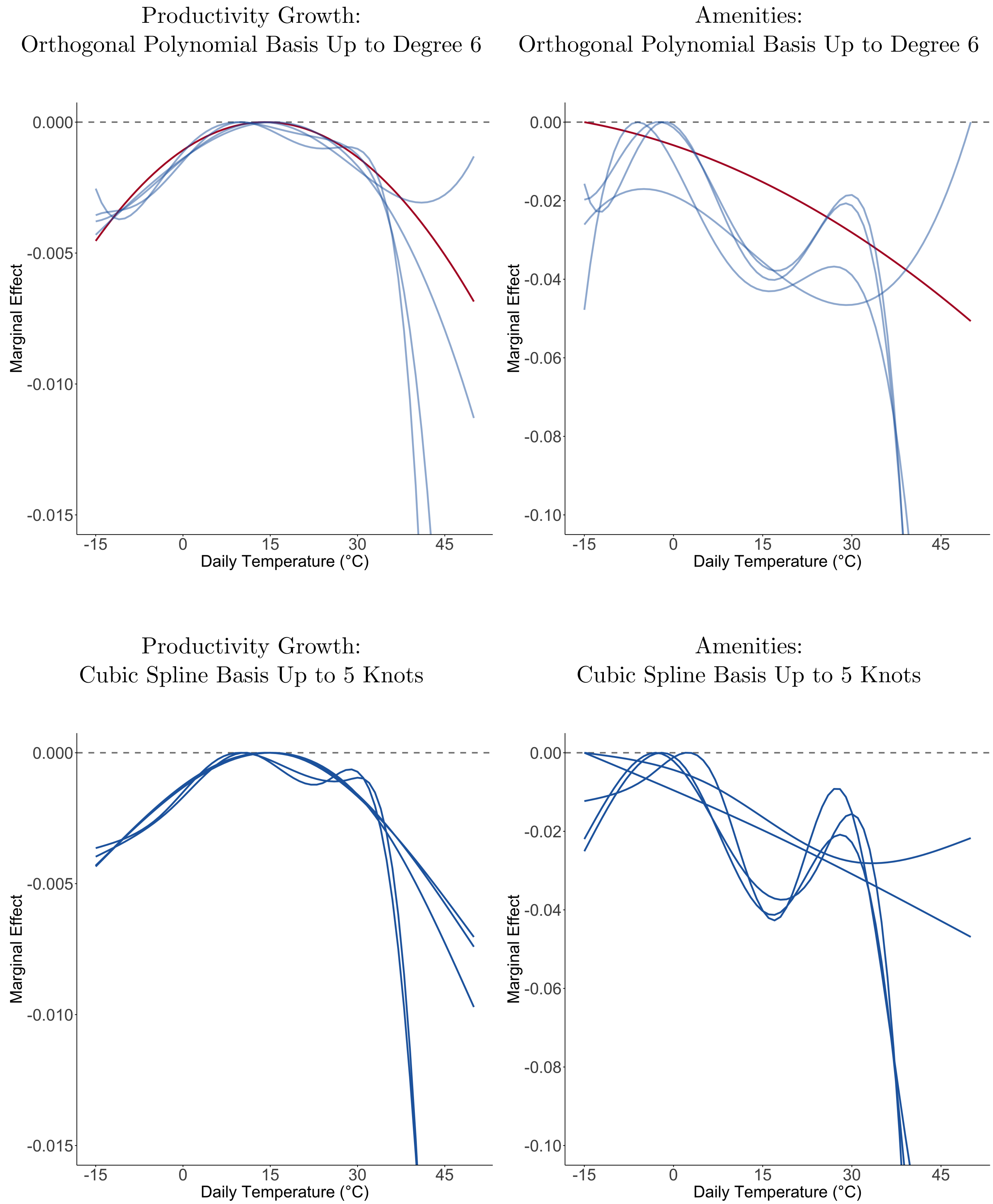
Note: The left panel shows the welfare impact of climate change as a percent of consumption with no amenities, homogeneous response functions, no input-output loops, and no changes in trade, migration, or industry switching in response to climate change. The counterfactual scenario is if the annual temperature distribution for each location was held constant at its 2000 level for 2015–2100. Both the baseline and counterfactual are simulated for 2101–2200 with constant fundamentals ($\dot{Z}^k_{i,t} = 1$ for all i, k) to allow the full impacts of the shocks to unfold.

Figure A4: The direct welfare value of amenities: climate shocks during 2015–2100.



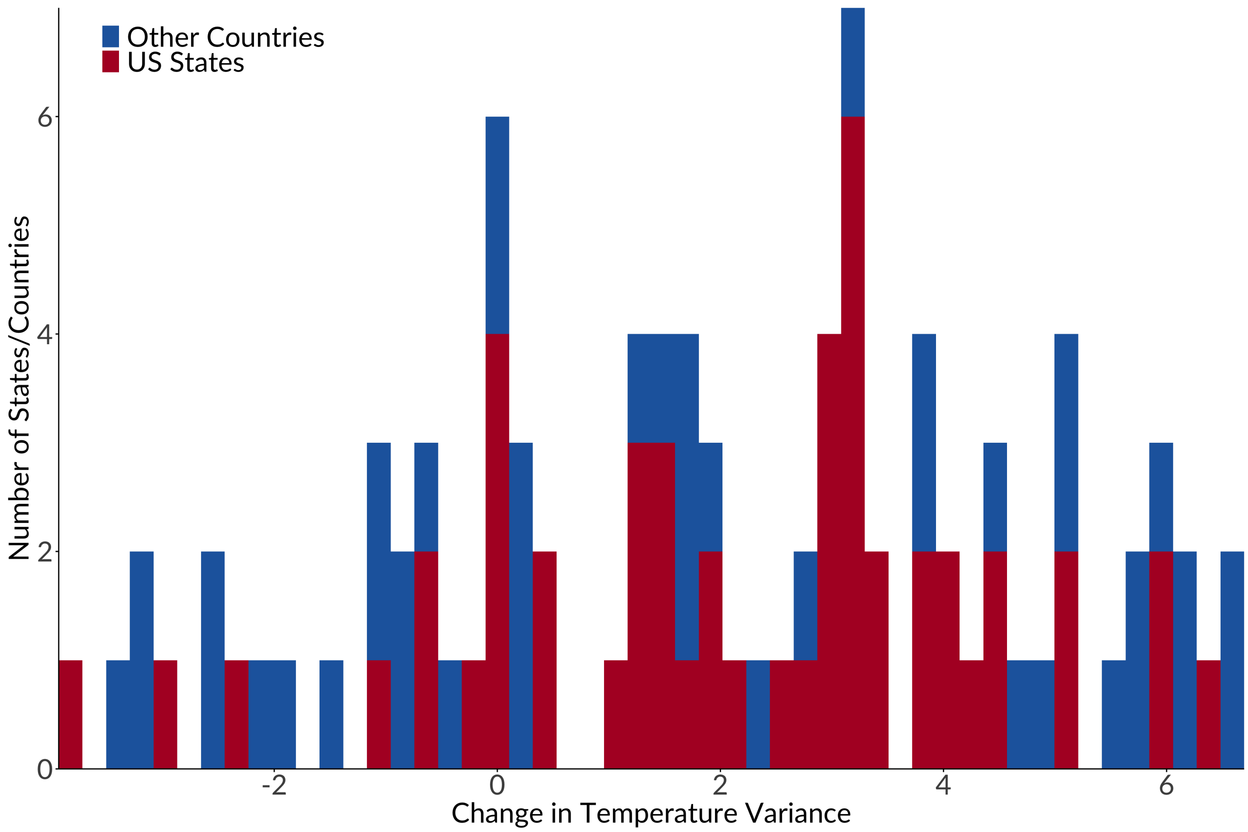
Note: The values on the map plot the direct climate impacts on amenities from equation (40). The map corresponds to our full model with productivity shocks, amenity shocks, local structures, and input-output loops

Figure A5: Productivity growth and amenity response functions under alternative polynomial and cubic spline approximations.



Note: The top left panel shows the growth response functions for sets of polynomials from degree 2 to 6. The red line is our preferred specification in the main text. The top right panel shows the amenity response functions for sets of polynomials from degree 2 to 6. The red line is our preferred specification in the main text. The bottom left panel shows the growth response functions for cubic splines with 1 to 5 evenly spaced knots. The bottom right panel shows the amenity response functions for cubic splines with 1 to 5 evenly spaced knots.

Figure A6: The change in within-year temperature variability from 2015–2024 to 2091–2100.



Note: The values are the change in within-year daily temperature variance from the first ten years of the SSP2-4.5 simulation to the last ten years.