

On the Spatial Economic Impact of Global Warming*

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Abstract

We propose a dynamic spatial theory to analyze the geographic impact of climate change. Agricultural and manufacturing firms locate on a hemisphere. Trade across locations is costly, firms innovate, and technology diffuses over space. Energy used in production leads to emissions that contribute to the global stock of carbon in the atmosphere, which affects temperature. The rise in temperature differs across latitudes and its effect on productivity also varies across sectors. We calibrate the model to analyze how climate change affects the spatial distribution of economic activity, trade, migration, growth, and welfare. We assess quantitatively the impact of migration and trade restrictions, energy taxes, and innovation subsidies.

1. INTRODUCTION

The potential negative economic effects of anthropogenic temperature increases are the result of frictions that prevent the free movement of goods and people in space. The logic and evidence behind this claim is straightforward. Temperature varies by parallel from 0° celsius in the North Pole to 28° celsius in the Equator (during the growing season). This range is much larger than the estimates of temperature increases in extreme scenarios, that reach at most between 6° and 8° celsius over the next 200 years. Hence, over this time period, the increase in temperature will induce more moderate temperatures in large parts of the world, thereby increasing productivity in those regions. Of course, under these same scenarios, global warming will also create large deserts in which no agricultural or manufacturing production will be feasible. Combine these observations with the fact that most land in the world is essentially economically unused and empty. According to G-Econ 4.0, in 2005 at market exchange rates 90% of production occupied only 10% of land. The number is 84% in PPP terms and 72% if we focus on population. The extreme concentration of production and population implies that if we expect large economic losses from global warming, those cannot come just from the direct effect of temperature increases on the productivity of land. Since most of land is unused, making a fraction of it unfit for production would not by itself lead

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to large losses in output. Instead, any substantial cost of climate change must be associated with the frictions involved in moving production and people from their current sites to the regions that will be suitable for production in the future. Understanding how these frictions affect the impact of global warming is the primary goal of this paper.

Global warming has had an important effect on the geography of economic activity already in the past. During the Medieval Warm Period, roughly between the ninth and fourteenth centuries, the world experienced temperatures rises of up to 2° celsius that, according to Fagan (2008) “...brought bounty to some areas, but to others, prolonged droughts that shook established societies to their foundations.”¹ Northern Europeans and Inuits benefitted enormously, while Mongols, native Americans, and other Mesoamerican societies suffered losses that went from limiting their expansion to bringing them to the brink of extinction. The world as we know it today was shaped by these changes, not because warming led to less available land or resources in the world as a whole, but because of the changes in the location of the suitable areas for production and growth. As we emphasize here for the case of future anthropogenic global warming, during the Medieval Warm Period Fagan (2008) concludes that “The only protection against such disasters was movement.”² Moving goods and people is restricted and costly, and the economic effect of temperature change will depend crucially on the magnitude of these frictions.

Understanding the spatial implications of global warming requires a framework with both geography as well as dynamics. The economic models that have been proposed to study the economic implications of temperature change are in general dynamic, but have not incorporated geographically ordered space. Some frameworks, such as Krusell and Smith (2009) and Nordhaus (2010), do include many regions, but these regions are not linked to each other through trade costs and technology diffusion. Hence, it is impossible to use them to understand changes in geographic specialization and trade patterns, as well as the geography of innovation and migration.

Incorporating a rich set of spatially ordered locations in a dynamic model is in general intractable. In Desmet and Rossi-Hansberg (2013) we develop a framework with both a spatial and a time dimension that can be solved forward due to local competition for land and technological diffusion. With the proposed structure, innovations yield profits for the firm today, but only increases in land values, not in profits, in the future. This property of the model implies that a firm’s dynamic optimization problem can be solved as a sequence of static problems. Hence, the equilibrium of the model is just a sequence of static spatial equilibria with state variables that follow laws of motion determined contemporaneously. This structure of the model makes the framework computable and suitable for the problem at hand.

To study the impact of global warming on spatial and aggregate outcomes we model the Northern Hemisphere. So space is half a sphere with the diameter of the earth. We study symmetric spatial equilibria where prices and allocations are identical for all locations at a given latitude. This is natural since we assume that all regions in a given latitude have the exact same temperature. The model features two industries, agriculture and manufacturing, whose productivity depends on both temperature and the local technology in the sector. The local technology is the result

¹See page 129 in Fagan (2008).

²See page 80 in Fagan (2008).

of technological innovations in the region as well as technological diffusion over space. In that sense, our model is a spatial endogenous growth model. Goods can be traded across locations subject to iceberg transport costs that depend on distance. Since space is continuous, incomplete specialization can happen only in a set of measure zero, and so it does not represent a problem to our focus on symmetric equilibria.

Agriculture and manufacturing firms produce using labor, land, and energy as inputs. Energy use generates a global stock of pollution (or CO_2 in the atmosphere), which in turn leads to temperature change. The increases in temperature that result from a larger stock of CO_2 in the atmosphere are not uniform across locations. As documented by the Intergovernmental Panel on Climate Change (IPCC, 2007), locations in latitudes closer to the North Pole increase their temperature more than those close to the Equator, although never enough to compensate for the larger temperatures close to the Equator. Obviously, since emissions are local but lead to a global stock of pollution, which in turn changes local temperatures, global warming is affected by an externality in energy use. Absent policy, local producers do not internalize the effect of their emissions on temperature change.

Temperature change has two main effects on spatial production patterns. First, the gradual increase in average temperatures makes the ideal location to produce in both industries move to the north over time. The literature suggests that the impact of temperature on productivity is more pronounced in agriculture than in manufacturing. Nevertheless, general equilibrium effects imply that the specialization areas in manufacturing change as well. These changes in specialization lead to changes in technology innovation in the different locations, thus amplifying the effects. The second implication of temperature change is that locations closer to the North Pole experience larger changes in temperatures, which enhances their comparative advantage in agriculture. Hence, temperature changes tend to favor specialization of the north in agriculture and the south in manufacturing. This is balanced by the fact that technologies in manufacturing are initially better in the northern latitudes, which leads to more innovation in the north. In calibrated examples, we observe that when the effect of pollution on temperature is small, the south specializes in agriculture and the north in manufacturing, as is roughly the case in the world today. In contrast, when the effect of CO_2 on temperature is large, the south increasingly specializes in manufacturing and produces in this sector using backward technologies with low total factor productivity. Eventually, if the effect is very large or if we study a very long period, the North Pole ends up specializing in agriculture.

The effects outlined above lead to large migrations of agents across locations, and so the consequences of global warming are mediated by the ability of agents and goods to move across space. We analyze two scenarios for labor mobility: one in which labor is freely mobile across locations and therefore welfare in the world is equalized, and another scenario where labor is freely mobile within a southern region and within a northern region (modeled as intervals of latitudes) but not across them. The first scenario is useful to understand the direction and the magnitude of migration patterns across countries. The second scenario is useful to understand the welfare implications of the spatial inequities created by global warming. Reality surely lies in between these two extremes. The framework is amenable to studying other less draconian migration regimes, although we leave that for future work. The quantitative exercises show that migration policy is a crucial comple-

mentary policy when addressing the impact of global warming. Migration restrictions increase the overall welfare costs of a more pronounced relationship between temperature and CO₂ emissions. Furthermore, they increase the negative effects of global warming in scenarios where the relationship between pollution and temperature is extreme and lead to significant costs in the south and significant gains in the north. Thus, global warming seems particularly problematic in the presence of migration restrictions.

The framework can be used to evaluate a variety of environmental, industrial, regional, and migration policies. Since we model the local decision to use energy in the production process, we can introduce either carbon taxes or cap-and-trade type policies. Since regional-sectoral innovation is endogenous, we can also introduce innovation incentives that reduce the use of energy. In the main formulation of the model, we use a Cobb-Douglas specification and so we do not allow for energy-biased technological changes. Nevertheless, technological innovations reduce the use of energy per unit of output and so, given a positively sloped supply of energy in the world, the quantity of energy used in equilibrium. Hence, local innovation affects energy use, pollution, and global warming. In that sense, innovation generates a positive externality. This externality is valued differently across regions. In the quantitative exercises, we explore the role of trade policy, energy taxes, and innovation subsidies. We find energy taxes to be particularly effective, as they tend to stimulate innovation by favoring high productivity locations, which tend to innovate more. The elasticity of welfare with respect to the energy tax is positive but declining in the tax and eventually turns negative. This pattern justifies carbon taxes that are several times larger than the ones found in studies that do not include adaptation through mobility. More generally, we find that these policies interact with innovation and the spatial pattern of economic activity, and so modeling space is essential to evaluate their aggregate implications.

Our model inevitably leaves out a number of relevant features of global warming. In addition to the increase in mean temperature, climate change is expected to cause rising sea levels, changes in precipitation, and more extreme weather patterns. Another important point is that lowering frictions is not simply a question of liberalizing migration policy. Historical evidence shows that large-scale migration due to rising temperatures has often been accompanied by substantial increases in violence (Hsiang, Burke and Miguel, 2013). The cost of moving should also include the difficulty or inability of moving physical capital. Local technology, which can be broadly interpreted as including local infrastructure and other local structures, partly addresses this issue in our setup. Furthermore, the fact that capital depreciates over time, makes its location less relevant over long periods of time. By abstracting from some of these elements, the quantitative implications of our policy analysis are necessarily somewhat stylized and imprecise. Our numbers should therefore be interpreted as baseline estimates obtained from a model that incorporates some of what we believe are the most relevant margins of adjustment to climate change: migration, trade, and innovation. These estimates will have to be revised and fine-tuned as the literature progresses.

In recent years there has been a vast effort to quantitatively model the economic effects of climate change. One of the main contributors has been Nordhaus (2008, 2010), who, building on his previous work, has developed a multi-region economic growth model of climate change that aims to quantitatively assess the impact of different abatement policies. We draw on his

work to incorporate some of the relevant features of climate change, such as the link between production, emissions, carbon stock, and temperature. The calibration part of our paper also partly follows the RICE/DICE models by Nordhaus, which we further complement with insights from the Intergovernmental Panel on Climate Change (IPCC) and studies on the impact of temperature on crop yields (Le, 2010; Lobell and Burke, 2010). Where we deviate from Nordhaus (2008, 2010) is by considering space to be ordered and by introducing more than one sector. This allows us to analyze the role of trade, specialization, migration and agglomeration in mediating the impact of climate change on the spatial distribution of economic activity and on welfare. There are a few papers that explicitly introduce space into models of climate change. An example is the work by Brock et al. (2012a,b), which focuses on how space matters to model heat diffusion across latitudes and the moving of the ice lines toward the poles.

There have been some attempts to incorporate trade and specialization into the analysis of climate change, such as the IMPACT model developed by the International Food Policy Research Institute (IFPRI), as well as the EPPA model described in Babiker et al. (2008), among others. Nearly all of these attempts to model trade in combination with climate change use Armington assumptions and therefore are not suitable to analyze the effect of climate change on patterns of specialization and local innovation over time. One of the only exceptions is the IMPACT model, which focuses solely on agriculture and is therefore partial equilibrium in nature (Nelson et al., 2009). Purely empirical studies on the impact of climate change on agriculture that incorporate the possibility of switching between different crops, or other ways of adapting, are more abundant (Mendelsohn, Nordhaus and Shaw, 1994; Deschênes and Greenstone, 2007; Fisher et al., 2012; Burke and Emerick, 2013). In a similar vein, but using a model, recent work by Costinot, Donaldson and Smith (2012) rely on high-resolution data to analyze the expected changes in comparative advantage for different crops, and the implied aggregate welfare changes. Because these studies do not identify or incorporate particular forms of adaptation like migration, they cannot assess how this adjustment feeds back into future climate change. This is the general equilibrium feedback which requires a model like the one we propose.

Our paper is part of an incipient literature that quantitatively assesses the economic impact of climate change in standard dynamic general equilibrium models. Examples include Hassler and Krusell (2012) and Golosov et al. (2013), who incorporate climate change into an otherwise standard macroeconomic model and quantitatively analyze the impact of different tax policies. We follow in the same tradition but focus on trade and innovation and consider space to be ordered. Macroeconomists have also become increasingly interested in analyzing how policy can be used to make growth sustainable. For example, Acemoglu et al. (2012) and Aghion et al. (2011) analyze which types of policies can direct technological change toward the use of clean energy. In our model, there is no choice between clean and dirty energy, but policy does affect the intensity of energy use and thus the amount of pollution.

The sensitivity analysis we carry out in the paper is motivated by different concerns raised in the literature. One issue, highlighted by von Below and Persson (2008) and Weitzman (2009), is the substantial uncertainty about the relations between economic activity and global warming, including the possibility of catastrophic climate change. We will compare how the sensitivity in the

relation between pollution and temperature affects outcomes. Another hotly debated question is which discount factor to use, as welfare effects depend crucially on the value chosen for this parameter. The *Stern Review* (Stern, 2006), for example, came under criticism for using a high discount factor. In our numerical simulations we will compare outcomes considering different discount rates.

The rest of the paper is organized as follows. Section 2 describes the model and Section 3 discusses the calibration. Section 4 carries out the benchmark numerical simulation and analyzes the impact of global warming by comparing economies where pollution has distinct effects on temperature. Section 5 assesses the impact of migration and trade barriers, and Section 6 studies the effect of energy taxes and innovation subsidies. Section 7 concludes. An appendix explores alternative formulations of the link between emissions and temperature.

2. THE MODEL

The economy consists of land and agents located in a half sphere that represents the Northern Hemisphere. Any point in the half sphere can be represented by its latitude ($\ell_V \in [0, \frac{\pi}{2}]$) and longitude ($\ell_H \in [-\pi, \pi]$). We will focus on symmetric allocations from the North Pole and so a location's characteristics will only depend on its latitude. It is useful to define $\tilde{D}(\ell_V)$ as the circumference of the Earth at latitude ℓ_V in kilometers. For simplicity we assume that the Earth is a perfect sphere with radius at the Equator of $r_E = 6,371$ km. Hence $\tilde{D}(\ell_V) = 2\pi r_E \sin(\pi/2 - \ell_V)$, so at the North Pole ($\ell_V = \pi/2$), $\tilde{D}(\pi/2) = 0$ km, and at the Equator ($\ell_V = 0$), $\tilde{D}(0) = 2\pi r_E = 40030$ km, namely, the circumference of the Earth.

The total surface in the Northern Hemisphere is then given by the integral over a density given by the circumference, namely,

$$\int_0^{\pi/2} 2\pi r_E \sin(\pi/2 - \ell_V) r_E d\ell_V = 2\pi r_E^2 \cos(\pi/2 - \ell_V) \Big|_0^{\pi/2} = 2\pi r_E^2 = 255032236 \text{ km}^2.$$

A fraction of 71% of the surface of the Earth is covered with water. The fraction is, of course, heterogeneous at different latitudes. We abstract from this heterogeneity and multiply the surface at all latitudes by 0.29. Hence, when we integrate over space we need to use the density $D(\ell_V) = 0.29 r_E \tilde{D}(\ell_V) = 0.58 \pi r_E^2 \sin(\pi/2 - \ell_V)$.

Countries in the Northern Hemisphere, when we use them, will be modeled as intervals of latitudes. So a country is supposed to occupy a whole ring of the earth. Note that all locations with the same latitude are ex-ante identical. Let there be N countries, where country $n = 1$ is the one closest to the Equator and occupies latitudes $[0, n_1]$, and country $n = N$ is the one closest to the North Pole and occupies latitudes $[n_{N-1}, n_N]$. Throughout we refer to a location as $\ell = (\ell_V, \ell_H) \in [0, \frac{\pi}{2}] \times [-\pi, \pi]$.

The total number of agents in country n is denoted by \bar{L}_n , and each of them is endowed with one unit of time each period. We let $\bar{L} = \sum_n \bar{L}_n$ denote the world's population. Agents are infinitely lived.

2.1. Preferences

Agents live where they work and they derive utility from the consumption of two goods: agriculture and manufacturing. Every period labor is freely mobile across locations within a country. In the benchmark quantitative exercise we allow also for mobility across countries. Independently of the migration assumption in place, throughout the paper we assume that agents can move freely across sectors and within countries.

Agents supply their unit of time inelastically in the labor market. They order consumption bundles according to an instantaneous utility function $U(c_A, c_M)$ with standard properties, where c_i denotes consumption of good $i \in \{A, M\}$. We assume that the utility function $U(\cdot)$ is homogeneous of degree one. In the numerical exercises below we use a CES utility function with an elasticity of substitution given by $1/(1 - \alpha)$, namely,

$$U(c_M, c_A) = (h_M c_M^\alpha + h_A c_A^\alpha)^{\frac{1}{\alpha}}.$$

Agents hold a diversified portfolio of land and firms in all locations.³ Goods are non-storable, and there is no other savings technology apart from land and firm ownership. The problem of an agent at a particular location ℓ in country n is given by⁴

$$\begin{aligned} & \max_{\{c_i(\ell, t)\}_0^\infty} (1 - \beta)E \sum_{t=0}^{\infty} \beta^t U(c_M(\ell, t), c_A(\ell, t)) & (1) \\ \text{s.t.} \quad & w(\ell, t) + \frac{\bar{R}(t) + \Pi(t)}{\bar{L}} = p_A(\ell, t) c_A(\ell, t) + p_M(\ell, t) c_M(\ell, t) \text{ for all } t \text{ and } \ell. \end{aligned}$$

where $p_i(\ell, t)$ denotes the price of good i , $w(\ell, t)$ denotes the wage at location ℓ and time t , $\bar{R}(t)$ and $\Pi(t)$ denote total land rents and total firm profits. Total firm profits, $\Pi(t)$, include standard profits (which are zero in equilibrium) and the value of the energy supply given by $e(t)E^S(e(t))$ where $e(t)$ represents the price of energy and $E^S(\cdot)$ its supply. Given that agents hold a diversified portfolio of land, firms, and energy in all locations, $\bar{R}(t)/\bar{L}$ and $\Pi(t)/\bar{L}$ represent the per agent dividend from land and firm ownership. The first-order conditions of this problem yield

$$U_i(c_A(\ell, t), c_M(\ell, t)) = \lambda(\ell, t) p_i(\ell, t), \text{ for all } i \in \{A, M\},$$

where $U_i(\cdot)$ is the marginal utility of consuming good i and $\lambda(\ell, t)$ is a location- and time-specific Lagrange multiplier. Denote by $\bar{U}_n(p_A(\ell, t), p_M(\ell, t), w(\ell, t) + (\bar{R}(t) + \Pi(t))/\bar{L})$ the indirect utility function of an agent at location ℓ in country n .

³Since $U(\cdot)$ is constant returns to scale, agents are not risk averse. If they were, they would like to hold this diversified portfolio to insure themselves against idiosyncratic local shocks. Alternatively we could have agents hold a diversified portfolio of land and assets in the country where they reside.

⁴Since we assume labor mobility within a country, utility levels within the country will equalize across space each period and so we can study the optimization problem of an agent as if she were to stay in the same location forever.

Free labor mobility across locations within countries in each period guarantees that

$$\bar{U}_n (p_A(\ell, t), p_M(\ell, t), w(\ell, t) + (\bar{R}(t) + \Pi(t)) / \bar{L}) = \bar{u}_n(t), \text{ for all } t \text{ and } \ell, \quad (2)$$

where $\bar{u}_n(t)$ is determined in equilibrium.

2.2. Technology

Firms specialize in one sector. The inputs of production are land, labor and energy. Production per unit of land in location ℓ at time t , if the location specializes in agriculture, is given by

$$Y_A(L_A(\ell, t), E_A(\ell, t)) = Z_A(\ell, t) g_A(T(\ell, t)) L_A(\ell, t)^{\mu_A} E_A(\ell, t)^{\sigma_A},$$

and, similarly, if it specializes in manufacturing is

$$Y_M(L_M(\ell, t), E_M(\ell, t)) = Z_M(\ell, t) g_M(T(\ell, t)) L_M(\ell, t)^{\mu_M} E_M(\ell, t)^{\sigma_M},$$

where $L_i(\ell, t)$ is the amount of labor per unit of land; $E_i(\ell, t)$ is the amount of energy per unit of land used at location ℓ and time t in sector i ; $1 - \mu_i - \sigma_i > 0$ is the share of land in sector i ; ⁵ and $Z_i(\ell, t) g_i(T(\ell, t))$ is the technology level, composed of two parts: $Z_i(\ell, t)$ is the result of the investment decisions by firms and $g_i(T(\ell, t))$ determines the effect on productivity of the local temperature, $T(\ell, t)$. The function $g_i(T(\ell, t))$ is such that $g_i(T) \geq 0$ and $\lim_{T \rightarrow \infty} g_i(T) = \lim_{T \rightarrow -\infty} g_i(T) = 0$. Furthermore it is single-peaked and twice differentiable in the interior. Hence, there exists some finite ideal temperature T^* such that $g_i(T^*) \geq g_i(T)$ for all $T \in \mathbb{R}$. We use the following parametrization in the empirical exercise,

$$g_i(T) = \max \{g_{i0} + g_{i1}T + g_{i2}T^2, 0\}$$

where $g_{i0} \geq 0$, $g_{i1} > 0$ and $g_{i2} < 0$. So the ideal temperature is given by $T_i^* = -\frac{g_{i1}}{2g_{i2}}$ and yields $g_i(T_i^*) = g_{i0} - \frac{g_{i1}^2}{4g_{i2}}$.

2.3. Diffusion

Technology diffuses between time periods. This diffusion is assumed to be local and to decline exponentially with distance. In particular, if $Z_i(r, t-1)$ was the technology used in location r in period $t-1$, in the next period, t , location ℓ has access to (but does not necessarily need to use) technology

$$e^{-\delta \|\ell - r\|} Z_i(r, t-1),$$

⁵ A share of land smaller than one ($1 - \mu_i - \sigma_i$) is the main congestion force in our model. It implies that there are decreasing returns to scale in production in any particular location.

where $\|\ell - r\|$ denotes the distance between locations ℓ and r which is given by

$$\|\ell - r\| = r_E \arccos(\sin \ell_V \sin r_V + \cos \ell_V \cos r_V \cos(\ell_H - r_H)).$$

Hence, before the innovation decision in period t , location ℓ has access to

$$Z_i(\ell, t) = \max_{r \in [0, \pi/2] \times [-\pi, \pi]} e^{-\delta \|\ell - r\|} Z_i(r, t - 1) \quad (3)$$

which of course includes its own technology in the previous period. This type of diffusion is the only *exogenous* source of agglomeration in the model.

2.4. Innovation

A firm can decide to buy an innovation $\phi \geq 1$ at cost $\psi_i(\phi)$ per unit of land in a particular industry i (this cost will be paid using local production so the real cost in industry i is given by $\psi_i(\phi)/p_i(\ell, t)$ per unit of land). Hence, a firm that obtained a productivity $Z_i(\ell, t)$ in the morning of period t after diffusion happened, and chooses a level of innovation ϕ , will improve its technology to $\phi Z_i(\ell, t)$. We assume that $\psi_i(\phi)$ is twice continuously differentiable, $\psi_i'(\phi) > 0$, $\psi_i''(\phi) > 0$ for $\phi > 1$, and $\lim_{\phi \rightarrow \infty} \psi_i'(\phi) = \infty$ with, potentially, $\psi_i(1) > 0$.

In the calibration below we index the cost by the wage so that it scales with the economy and use the following specification,

$$\psi_i(\phi) = w(\ell, t) \xi_i \frac{\phi^{1+\gamma_i} - 1}{1 + \gamma_i}.$$

2.5. The Dynamics of Temperature

We now discuss how emissions from global production affect the carbon stock and how the carbon stock determines temperature in different locations. The first link, between emissions and the carbon stock, is known as the carbon cycle. It analyzes how carbon flows between different reservoirs (the atmosphere, the upper ocean, and the lower ocean). These flows determine how anthropogenic carbon emissions affect the total stock of carbon in the atmosphere, and how this effect decays over time as emitted carbon slowly gets trapped in the lower oceans. The second link, between the carbon stock and temperature, is the climate sensitivity. As carbon accumulates in the atmosphere, this generates increased radiative forcing, leading to higher temperatures.

The literature has used different ways of modeling these links. On the one hand, Nordhaus (2010) assumes a carbon cycle in which the effect of emissions on the atmospheric carbon stock completely dies out over time. Emissions initially add to the carbon stock in the atmosphere, but this effect slowly decays as the emitted carbon gradually moves to the lower oceans, to then remain there forever. On the other hand, Allen et al. (2009) and Matthews et al. (2009) show that both links, the carbon cycle and the climate sensitivity, can be simplified into a direct linear relation

between cumulative emissions and temperature. This amounts to assuming zero decay in the effect of emissions on temperature. In between those two extremes, Golosov et al. (2013) follow Archer (2005) and propose a carbon cycle in which about 20% of emissions stay in the atmosphere forever, whereas the remaining part decays over time.

We assume a simplified reduced-form carbon cycle in the spirit of Nordhaus (2010), where the carbon stock slowly decays over time. In other words, the stock of carbon in the atmosphere in a given period depends on the stock of carbon in the atmosphere in the previous period and on the emissions created by energy use in manufacturing and agriculture. So let the global stock of carbon be given by

$$P(t+1) = \varepsilon_1 P(t) + \varepsilon_2 (\bar{E}_A(t) + \bar{E}_M(t)), \quad (4)$$

where $\varepsilon_1 \leq 1$ determines how the stock of carbon in the atmosphere decays over time, whereas ε_2 determines how a unit of energy is converted in a unit of carbon emissions. Note that $P(0)$ is normalized to 0. If we were to set $\varepsilon_1 = 1$, then $P(t)$ could be interpreted as cumulative emissions, rather than as the stock of carbon. This implies that the model of Allen et al. (2009) and Matthews et al. (2009) is a special case of ours. Although for our baseline analysis we assume $\varepsilon_1 < 1$, in Appendix we will redo our numerical analysis using the Allen et al. (2009) assumption of $\varepsilon_1 = 1$. The aggregate energy consumed in sector i is given by

$$\bar{E}_i(t) = \int_0^{\pi/2} \theta_i(\ell, t) E_i(\ell, t) D(\ell) d\ell$$

where $\theta_i(\ell, t)$ denotes the fraction of land at location ℓ that specializes in sector i at time t . We abstract from household consumption of energy.

The next step is to determine the temperature $T(\ell, t)$ as a function of the stock of carbon. In Nordhaus (2010) and Golosov et al. (2013) temperature is a concave (logarithmic) function of the stock of atmospheric carbon, whereas in Allen et al. (2009) and Matthews et al. (2009) temperature is a linear function of cumulative emissions. Consistent with this, we assume temperature to be weakly concave in P . In addition, the environmental evidence seems to suggest that for a given increase in the level of aggregate pollution, locations farther to the north will experience a larger increase in temperatures (IPCC, 2007). Of course, independently of the stock of carbon, $T(\ell, t)$ is a decreasing function of ℓ , namely, temperatures at the Equator are always higher. A convenient way of parameterizing these different pieces of evidence is

$$T(\ell, t) = T(\ell, 0) + \nu_1 P(t)^{\nu_2} (1 - \nu_3 T(\ell, 0)) \quad (5)$$

for $0 < \nu_1, \nu_3 < 1$ and $0 < \nu_2 \leq 1$, where we choose some function $T(\cdot, 0)$ such that $\partial T(\ell, 0) / \partial \ell < 0$

for all ℓ . Then,

$$\frac{\partial T(\ell, t)}{\partial P(t)} = \nu_1 \nu_2 P(t)^{\nu_2 - 1} (1 - \nu_3 T(\ell, 0)) > 0 \quad (6)$$

$$\frac{\partial T(\ell, t)}{\partial \ell} = \frac{\partial T(\ell, 0)}{\partial \ell} (1 - \nu_1 \nu_3 P(t)^{\nu_2}) < 0 \quad (7)$$

if $(1 - \nu_1 \nu_3 P(t)^{\nu_2}) > 0$ and

$$\frac{\partial^2 T(\ell, t)}{\partial P(t) \partial \ell} = -\frac{\partial T(\ell, 0)}{\partial \ell} \nu_1 \nu_2 \nu_3 P(t)^{\nu_2 - 1} > 0. \quad (8)$$

In the calibration we choose values of ν_1 , ν_2 , and ν_3 to guarantee these properties.⁶

The value of ν_1 will play an important role in our quantitative exercises below. It will be our main way of modulating the importance of global warming. Given ν_2 , ν_3 , and $T(\ell, 0)$, a high ν_1 implies, by the derivative in (6), that temperature increases faster with pollution. Since pollution affects the real economy only through its effect on temperature, this implies that when $\nu_1 = 0$, there is no global warming phenomenon, and when ν_1 is large, pollution can lead to catastrophic increases in temperature.

While in our baseline analysis we will assume emitted carbon decays over time ($\varepsilon_1 < 1$ in equation (4)) and temperature is a strictly concave function of the carbon stock ($\nu_2 < 1$ in equation (5)), we can easily take the Allen et al. (2009) approach and make temperature a linear function of cumulative emissions by setting $\varepsilon_1 = 1$ and $\nu_2 = 1$. We will explore the robustness of our results to this alternative model in the Appendix. Recall that in terms of how emissions affect temperature, our baseline model assumes the whole stock of carbon decays over time, Allen et al. (2009) and Matthews et al. (2009) assume zero decay, whereas Golosov et al. (2013) take an intermediate view. Therefore, by comparing our baseline to Allen et al. (2009) and Matthews et al. (2009), we capture the full range of possibilities.

2.6. Firm's Problem

Firms maximize the expected present value of profits. The objective function of a firm in a given location ℓ at time t_0 is therefore

$$\max_{\{\phi_i(\ell, t), L_i(\ell, t), E_i(\ell, t)\}_{t=t_0}^{\infty}} \sum_{t=t_0}^{\infty} \beta^{t-t_0} \left[\begin{array}{l} p_i(\ell, t) \phi_i(\ell, t) Z_i(\ell, t) g_i(T(\ell, t)) L_i(\ell, t)^{\mu_i} E_i(\ell, t)^{\sigma_i} \\ -w(\ell, t) L_i(\ell, t) - e(t) E_i(\ell, t) - R(\ell, t) - \psi_i(\phi_i(\ell, t)) \end{array} \right], \quad (9)$$

⁶ At a small cost in the simplicity of the specification we could eliminate one of the three parameters in this equation. In the next section we calibrate and fix ν_2 and ν_3 throughout the paper and study the effect of changes in ν_1 .

for $i \in \{A, M\}$, where $R(\ell, t)$ is the firm's bid rent and $e(t)$ is the price of energy, which is the same in all locations, since we assume no energy transport costs.⁷ Note that we use β to discount firm profits, since there is no storage technology or financial assets in our model. In any case, given the argument below, this choice is irrelevant in our setup.

Labor is freely mobile within a country and firms compete for land and labor every period with potential entrants that, because of diffusion, have access to the same technology as they do. Hence, the decision of how many workers to hire, how much energy to use and how much to bid for land is a static problem. So, consider first a firm's static problem of choosing labor and energy in sector $i \in \{A, M\}$ at location ℓ and time t ,

$$\max_{L, E} p_i(\ell, t) \hat{\phi}_i(\ell, t) Z_i(\ell, t) g_i(T(\ell, t)) L^{\mu_i} E^{\sigma_i} - w(\ell, t) L - e(t) E, \quad (10)$$

where $\hat{\phi}_i(\ell, t)$ denotes the optimal innovation decision. Denote the firm's choice of labor per unit of land by $\hat{L}_i(\ell, t)$ and the choice of energy per unit of land by $\hat{E}_i(\ell, t)$. Then, given our Cobb-Douglas production function specification

$$\frac{w(\ell, t) \hat{L}_i(\ell, t)}{p_i(\ell, t) Y_i(\hat{L}_i(\ell, t), \hat{E}_i(\ell, t))} = \mu_i$$

and

$$\frac{e(t) \hat{E}_i(\ell, t)}{p_i(\ell, t) Y_i(\hat{L}_i(\ell, t), \hat{E}_i(\ell, t))} = \sigma_i.$$

The maximum per unit land rent that a firm in sector i is willing to pay at time t , the bid rent, is given by

$$R_i(\ell, t) = p_i(\ell, t) \hat{\phi}_i(\ell, t) Z_i(\ell, t) g_i(T(\ell, t)) \hat{L}_i(\ell, t)^{\mu_i} \hat{E}_i(\ell, t)^{\sigma_i} - w(\ell, t) \hat{L}_i(\ell, t) - e(t) \hat{E}_i(\ell, t) - \psi_i(\hat{\phi}_i(\ell, t)), \quad (11)$$

which guarantees that firms make zero profits.

Since profits are zero every period, the decision to innovate by the firm does not consider any future periods and is static. This is due to the presence of a competitive market for land and the fact that any firm can access the new technologies next period via diffusion. However, the innovation decisions are not socially optimal given the externality (see Desmet and Rossi-Hansberg (2013) for details). Hence, the innovation problem of a firm, given factor prices and the amount of labor, is given by

$$\max_{\hat{\phi}_i} p_i(\ell, t) \hat{\phi}_i Z_i(\ell, t) g_i(T(\ell, t)) \hat{L}_i(\ell, t)^{\mu_i} \hat{E}_i(\ell, t)^{\sigma_i} - \psi_i(\hat{\phi}_i). \quad (12)$$

⁷The assumption simplifies the model considerably. Modeling the location of energy production would be inconsequential for our results in the absence of scale economies in the sector.

Therefore

$$p_i(\ell, t) Z_i(\ell, t) g_i(T(\ell, t)) \hat{L}_i(\ell, t)^{\mu_i} \hat{E}_i(\ell, t)^{\sigma_i} = \psi_i'(\hat{\phi}_i(\ell, t))$$

which by the assumptions on $\psi_i(\cdot)$ has a unique solution. If $\psi_i(1) > 1$, we need to guarantee that

$$p_i(\ell, t) Z_i(\ell, t) g_i(T(\ell, t)) \hat{L}_i(\ell, t)^{\mu_i} \hat{E}_i(\ell, t)^{\sigma_i} > \frac{\psi_i(\hat{\phi}_i(\ell, t))}{(\hat{\phi}_i(\ell, t) - 1)},$$

otherwise $\hat{\phi}_i(\ell, t) = 0$.

2.7. Land, Goods, Energy, and Labor Markets

Goods are costly to transport. For simplicity we assume iceberg transport costs which are identical in agriculture and manufacturing. If one unit of any good is transported from ℓ to r , only $e^{-\kappa\|\ell-r\|}$ units of the good arrive in r . Since the technology to transport goods is freely available, the price of good i produced in location ℓ and consumed in location r has to satisfy

$$p_i(r, t) = e^{\kappa\|\ell-r\|} p_i(\ell, t). \quad (13)$$

Land in a given location is assigned to the firm in the industry that values it the most. Hence, land rents are such that

$$R(\ell, t) = \max\{R_A(\ell, t), R_M(\ell, t)\}. \quad (14)$$

If $R(\ell, t) = R_i(\ell, t)$ then $\theta_i(\ell, t) = 1$. To break ties, when $R_A(\ell, t) = R_M(\ell, t)$, we let $\theta_A(\ell, t) = 1$.

In order to guarantee equilibrium in product markets, we need to take into account that some of the goods are lost in transportation. Note also that this formulation implies that nothing in the allocation depends on the longitudinal angle of the location. So there is no trade across longitudes with the same latitude. Let $H_i(\ell, t)$ denote the stock of excess supply of product i between latitudes 0 and ℓ after summing over all longitudes. Define $H_i(\ell, t)$ by $H_i(0, t) = 0$ and by the differential equation

$$\frac{\partial H_i(\ell, t)}{\partial \ell} = \left[\theta_i(\ell, t) Y_i(\hat{L}_i(\ell, t), \hat{E}_i(\ell, t)) - \frac{\psi_i(\hat{\phi}_i(\ell, t))}{p_i(\ell, t)} - c_i(\ell, t) L(\ell, t) \right] D(\ell) - \kappa |H_i(\ell, t)|, \quad (15)$$

for any $\ell \in [0, \pi/2]$, where $L(\ell, t) = \sum_i \theta_i(\ell, t) \hat{L}_i(\ell, t)$ is total employment per unit of land. The equilibrium conditions in the goods markets are then given by

$$H_i(\pi/2, t) = 0 \text{ for all } i \text{ and } t.$$

The supply of energy in the world is given exogenously by $E^S(e(t)) = \varphi_1 e(t)^{\varphi_2}$ for $0 > \varphi_2 > 1$. Note that, even though we assume an upward sloping supply, we abstract from any energy extraction

costs, and so all revenue from selling oil is rebated to agents as explained when discussing the consumer problem in (1). Hence, market clearing in the energy sector implies

$$\bar{E}_A(t) + \bar{E}_M(t) = E^S(e(t)) \text{ for all } t. \quad (16)$$

The labor market equilibrium conditions for each country j and period t are given by

$$\sum_i \int_{n_{j-1}}^{n_j} \theta_i(\ell, t) \hat{L}_i(\ell, t) D(\ell) d\ell = \bar{L}_j, \quad (17)$$

where $j = 1, \dots, N$, $n_0 = 0$, and $n_N = \pi/2$.

2.8. Definition of Equilibrium

A competitive equilibrium in this economy is a set of real functions $(c_i, \hat{L}_i, \hat{E}_i, \theta_i, H_i, p_i, R_i, Z_i, \hat{\phi}_i, e, w, T)$ of locations $\ell \in [0, \pi/2]$ and time $t = 1, \dots$, for $i \in \{A, M\}$, and a set of utility levels \bar{u}_n such that:

- Agents solve the consumption problem in (1).
- Agents locate optimally, so (2) is satisfied.
- Firms maximize profits by choosing \hat{L}_i , \hat{E}_i , and $\hat{\phi}_i$ that solve (9), and by choosing the land bid rent, R_i , that solves (11).
- Land is assigned to the industry that values it the most, so if $\max\{R_A(\ell, t), R_M(\ell, t)\} = R_i(\ell, t)$, then $\theta_i(\ell, t) = 1$.
- Goods markets clear, so H_i is given by (15) and $H_i(\pi/2, t) = 0$.
- The worldwide energy market clears, so (16) is satisfied.
- The labor market in each country clears so (17) is satisfied.
- Technology Z_i satisfies (3) and technology becomes $\hat{\phi}_i Z_i$ when a location innovates.
- Temperature T is determined by (5).

3. CALIBRATION

The calibration strategy assigns parameter values so that the model matches certain key observations or predictions on climate change. Table 1 lists the parameter values and briefly explains how they were assigned. We now discuss our choices in some more detail.

The preference parameters that determine the weights of agriculture and manufacturing in the CES utility function, h_A and h_M , are set to match an initial employment share in agriculture of 35% (WDI, World Bank). For the elasticity of substitution between agriculture and manufacturing, we follow Yi and Zhang (2011) and choose a value of 0.5. Having an elasticity of substitution less

than one implies that the sector with higher productivity growth loses employment relative to the other sector.

The technology parameters require us to choose the factor shares of labor and energy in agriculture and manufacturing. Estimates of labor shares vary between 0.45 and 0.7 (Valentinyi and Herrendorf, 2008; Herrendorf and Valentinyi, 2012). Gollin et al. (2012) argue that, though somewhat higher in manufacturing, labor shares cannot be too different in both sectors. If not, this would lead to large differences in aggregate labor shares across poor and rich countries. Given that such differences are absent, we choose labor shares to be the same in both sectors and set them equal to 0.6. Estimates for the factor share of energy in agriculture come from Schnepf (2004), who estimates a figure of 0.05 for the United States. In developing countries the share is likely to be somewhat smaller (FAO, 2011), so we use a value of 0.04. In manufacturing, the International Energy Agency (2007) gives a figure of the energy cost as a share of the production cost of between 0.03 and 0.12, depending on the country. Taking an average, we use a value of 0.07.

The energy supply depends on its price. Using data from 1974 to 2004, Krichene (2005) estimates a long-run price elasticity of crude oil supply of 0.23 and a similar figure of 0.21 for natural gas. Brook et al. (2004) review several studies and find numbers ranging from 0.1 to 0.58. Based on these different studies, we set the price elasticity of energy supply, J_2 , to 0.25.⁸

For the transportation cost parameter, we rely on Ramondo and Rodriguez-Clare (2012), who assume that $\tau_{\ell r} > 1$ units must be shipped over a distance $|\ell - r|$ for 1 unit to arrive, where $\tau_{\ell r} = 1 + \tau_0 + \tau_{dist}|\ell - r|/1000$. Since in our model $e^{\kappa|\ell - r|}$ must be shipped for 1 unit to arrive, we substitute $\tau_{\ell r}$ for $e^{\kappa|\ell - r|}$. Therefore,

$$\kappa = \frac{\ln(1 + \tau_0 + \tau_{dist} \frac{|\ell - r|}{1000})}{|\ell - r|}.$$

Using their parameter estimates, this would give us a value of κ between 0.0007 and 0.0001. Given that Ramondo and Rodriguez-Clare (2012) include any costs that impede trade, and our benchmark model only has transport costs, we take a slightly smaller value of $\kappa = 0.00005$. In some of our policy exercises we will analyze the effect of other trade costs paid only at borders, such as tariffs, that would bring average trade costs closer to their estimates.

For technology diffusion, Comin, Dmitriev and Rossi-Hansberg (2012) analyze the adoption of 20 major technologies in 161 countries over the last 140 years. The median of their distance decay parameter gives a value of 1.5.⁹ Given that their estimates are based on distances of 1000 kilometers, this corresponds to a value of 0.0015 in our context, and so we set our δ parameter equal to this value.¹⁰

⁸The energy supply function, $J_1 e^{J_2}$, also includes a parameter J_1 . In the calibration we set J_1 to 10,000,000 but its value does not qualitatively affect any of the results.

⁹We exclude Rail-line Kms from the calculation of the median since the model in Comin, Dimitriev and Rossi-Hansberg (2012) fits that technology badly. Including it would yield a median of 1.3.

¹⁰Technology diffusion is modeled in a slightly different way in Comin et al. (2012), so their parameter estimates are not strictly comparable to ours. In their setup, adoption of a new technology depends on the probability of someone in location r meeting someone in location ℓ who has already adopted, where the probability of meeting declines with distance. Taking a more literal interpretation and transforming their estimates into what they imply for our estimates would give values for δ between 0.0012 and 0.0024, similar to the 0.0015 value used in our benchmark exercise.

Table 1. Parameter Values

Parameter	Target/Comment
1. Preferences: $U = (1 - \beta) \sum_{t=0}^{\infty} \beta^t (h_M c_M^\alpha + h_A c_A^\alpha)^{\frac{1}{\alpha}}$	
$\beta = 0.95$	Standard discount factor
$h_M = 1.45$	35% Initial employment share in agriculture (WDI, World Bank)
$h_A = 0.55$	35% Initial employment share in agriculture (WDI, World Bank)
$\alpha = -1$	Elasticity substitution agriculture - manufacturing (Yi and Zhang, 2011)
2. Technologies: $Y_M = Z_M g_M L_M^{\mu_M} E_M^{\sigma_M}$ and $Y_A = Z_A g_A L_A^{\mu_A} E_A^{\sigma_A}$	
$Z_M(\ell, 0) = 0.8 + 0.4\ell/90$	Specialization patterns by latitude (own calculations)
$Z_A(\ell, 0) = 1.2 - 0.4\ell/90$	Specialization patterns by latitude (own calculations)
$\mu_M = 0.6$	Valentinyi and Herrendorf (2008), Herrendorf and Valentinyi (2012)
$\sigma_M = 0.07$	International Energy Agency (2007)
$\mu_A = 0.6$	Valentinyi and Herrendorf (2008), Herrendorf and Valentinyi (2012)
$\sigma_A = 0.04$	Schnepf (2004), FAO (2011)
3. Energy supply: $E^S(e) = J_1 e^{J_2}$	
$J_2 = 0.25$	Long-run elasticity energy supply (Brook et al., 2004; Krichene, 2005)
4. Transportation (κ) and technology diffusion (δ)	
$\kappa = 0.00005$	Ramondo and Rodriguez-Clare (2012)
$\delta = 0.0015$	Comin, Dmitriev and Rossi-Hansberg (2012)
5. Temperature and Productivity: $g_i(T) = \max\{g_{i0} + g_{i1}T + g_{i2}T^2, 0\}$, $i \in \{A, M\}$	
$g_{M0} = 0.3$	Match population shares at different latitudes
$g_{M1} = 0.08$	
$g_{M2} = -0.0023$	
$g_{A0} = -2.24$	Relation temperature - yields (Lobell and Burke, 2010; Le, 2010)
$g_{A1} = 0.308$	
$g_{A2} = -0.0073$	
6. Innovation Cost: $\psi_i(\phi_i) = \xi_i w \frac{\phi_i^{1+\gamma_i} - 1}{1+\gamma_i}$, $i \in \{A, M\}$	
$\gamma_M = 120$, $\xi_M = 0.035$	2% average output growth (PWT 7.0, 2011)
$\gamma_A = 125$, $\xi_A = 0.016$	2% average output growth (PWT 7.0, 2011)
6. Carbon Cycle: $P(t+1) = \varepsilon_1 P(t) + \varepsilon_2 \bar{E}(t)$	
$\varepsilon_1 = 0.9975$	Nordhaus (2010)
$\varepsilon_2 = 0.000001374$	Increase in carbon by 800 GTC by 2100 (Nordhaus, 2010)
7. Temperature Increase by Latitude: $T(\ell, t) = T(\ell, 0) + \nu_1 P(t)^{\nu_2} (1 - \nu_3 T(\ell, 0))$	
$\nu_1 = 0.0003$	Current temperature Equator 28 degrees, poles 0 degrees
$\nu_2 = 0.5$	Increase by 2 degrees at Equator (IPCC, 2007)
$\nu_3 = 0.0238$	Increase by 6 degrees at pole (IPCC, 2007)
8. Population:	
$\bar{L} = 7,000,000$	World population 7 billion

For the link between temperature and productivity, our model assumes a quadratic relationship. Agronomists have estimated such quadratic relations between temperature and crop yields.¹¹ Le (2010) gives estimates for corn, cotton, soybean and sorghum for the U.S., whereas Lobell and Burke (2010) analyze maize in sub-Saharan Africa. Starting with Mendelsohn, Nordhaus and Shaw (1994), the literature has emphasized the possibility of adapting to climate change by switching between crops. We therefore take the envelope of the quadratic relations of the different crops. In particular, we take the average of the minimum and maximum optimal temperatures of the different crops (21.1 centigrade) and the minimum and maximum temperatures at which the implied yields of all crops become zero (9.4 centigrade and 32.9 centigrade). Using these three restrictions, and assuming a quadratic function between temperature and productivity, we solve out for the constant g_{A0} , the linear coefficient g_{A1} and the quadratic coefficient g_{A2} .

Few similar studies exist for the relation between temperature and the level of output in manufacturing.¹² In the absence of such a relation, the model would predict too many people living in arctic latitudes, specializing in manufacturing. However, in reality this is not the case. To see this, we use detailed geographic data on population for 2000 from the LandScan database (Oak Ridge National Laboratory, 2001) and split up the world by latitude into 1000 bands of 9.6 kilometers each (corresponding to 0.087 arc-degrees).¹³ For each band we then calculate the population as a share of the world’s population. Finally, since our model focuses on one hemisphere, we sum up southern and northern latitudes. Figure 1 shows the results by depicting population share by latitude, smoothed using an Epanechnikov kernel and including the 95% confidence intervals. As can be seen, the share of the world’s population living above the 66th parallel (corresponding to the Arctic Circle in the Northern Hemisphere) is close to zero. We therefore set the relation between temperature and manufacturing output to match this lower share of population living in arctic latitudes. The calibrated coefficients g_{M0} , g_{M1} and g_{M2} imply an optimal temperature for manufacturing production of 17.3 centigrade (compared to 21.1 in agriculture). In addition, the relation between temperature and productivity is also much flatter than in agriculture: positive productivity occurs over a range spanning -3 to 38 degrees centigrade (compared to a range spanning 9.4 to 32.9 degrees in agriculture).

In reality the share of oceans changes with latitude, whereas in the model it does not. As a result, one reason why the share of population in Figure 1 varies with latitude may be the varying share of oceans. To make sure this is not driving the results, we compute the population density by latitude by taking the total population within a latitudinal band and dividing it by total land area of that latitudinal band. As can be seen in Figure 2, the overall picture is very similar, so this does not seem to be an important issue.

¹¹In addition to average temperature, yields are also affected by other climatic factors, such as the number of days crops are subjected to different temperatures (Schlenker and Roberts, 2009), the minimum and maximum temperatures (Welch et al., 2010) and precipitation (Lobell and Burke, 2010). Incorporating these additional effects might be important, but challenging, so we leave this for future research.

¹²An exception is Hsiang (2010) who finds a negative impact of higher temperatures in non-agriculture in 28 Caribbean-basin countries, and relates this to the drop in labor productivity when workers suffer thermal stress. In related work, Dell, Jones and Olken (2012) provide estimates of the impact of temperature change on sectoral growth, but not of the relation between temperature and sectoral output.

¹³The 1000 bands of 0.087 arc-degrees do not add up to 90 degrees, because the most northern and southern

Figure 1. Population Share by Latitude

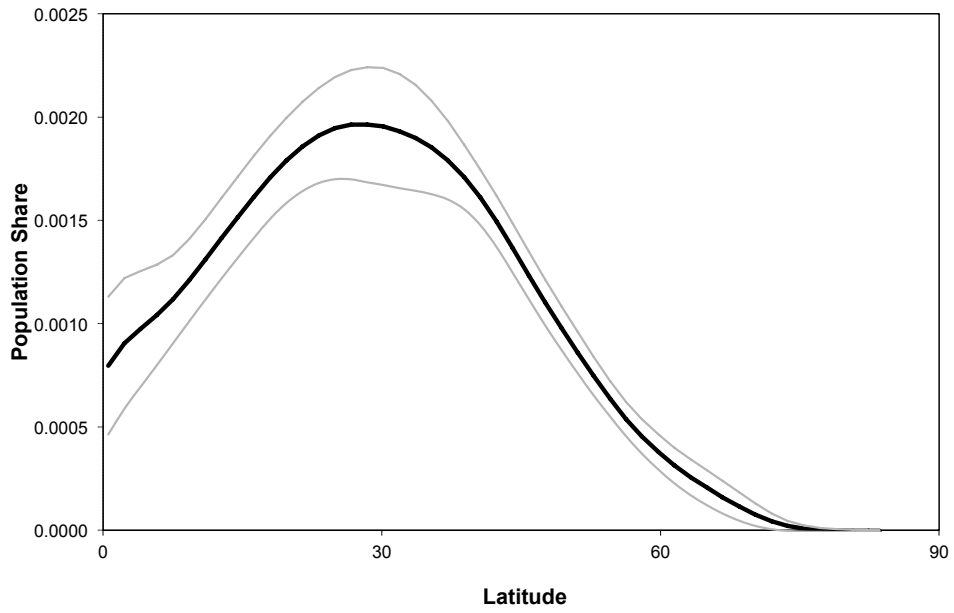
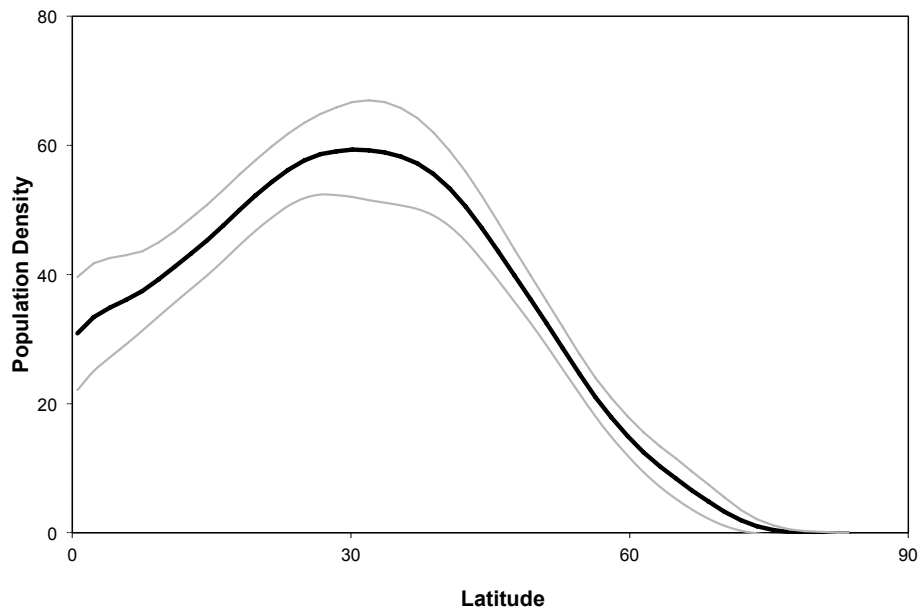
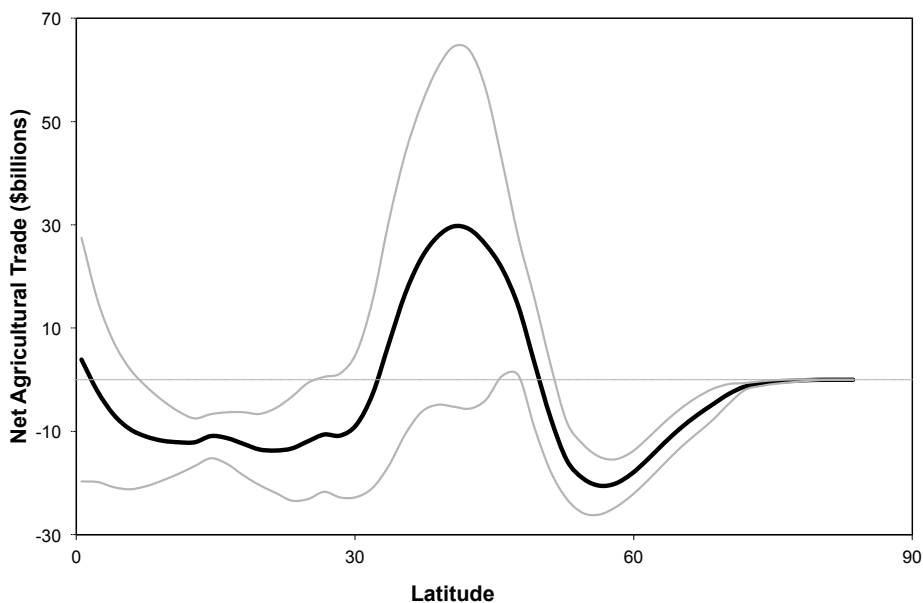


Figure 2. Population Density by Latitude



The lower optimal temperature and the smaller sensitivity of productivity to temperature in manufacturing imply that lower latitudes will mainly specialize in agriculture, and higher latitudes will mostly produce manufactured goods. The data counterpart requires us to look at trade patterns by latitude. To do so, we use sectoral trade data for 2000 from the NBER-United Nations Trade Data (Feenstra et al., 2005) and compute net agricultural trade by country.¹⁴ We take a fairly restrictive definition of agriculture, focusing mainly on crops, since they are the ones to which our temperature - yield relation applies.¹⁵ We then split up the world into 100 latitudinal bands and assign each country's net agricultural trade to the different latitudinal bands proportional to the country's population share living within the different latitudinal bands. Figure 3 depicts net agricultural exports at different latitudes.

Figure 3. Net Agricultural Exports by Latitude



As can be seen, the area located between the 30th and the 50th parallel specializes in agriculture. This corresponds, roughly speaking, to the regions from northern Mexico to southern Canada, North Africa to Central Europe, northern India to Kazakhstan, and southern Brazil to southern Argentina. Further away from the 50th parallel toward the polar regions, countries specialize mainly in manufacturing. In two areas net agricultural trade is close to zero. In the region going from the Equator to the 30th parallel, the main reason is the absence of a pronounced pattern of specialization, though there is a slight bias toward manufacturing. The other region with agricultural

latitudes are dropped, as no one lives there.

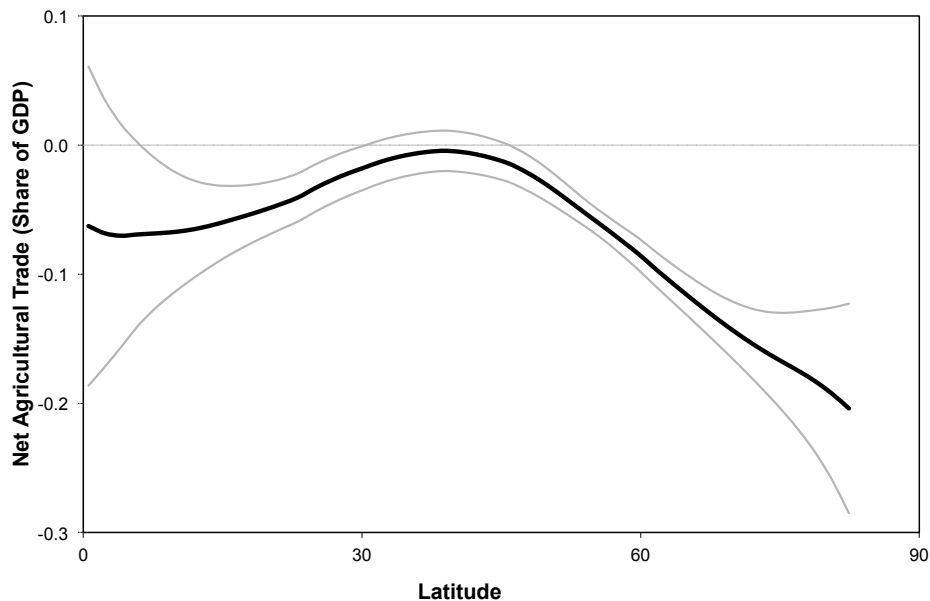
¹⁴Because not all countries have balanced trade, net agricultural exports are defined as (exports of agricultural - imports of agricultural goods) - (exports of non-agricultural goods - imports of non-agricultural goods).

¹⁵In particular, we define agriculture as SITC2 codes 04 (cereals and cereal preparations), 05 (vegetables and fruit), 06 (sugars, sugar preparations and honey), 07 (coffee, tea, cocoa, spices and manufactures thereof), 08 (feeding stuff for animals), 09 (miscellaneous edible products and preparations), 11 (beverages), 12 (tobacco and tobacco manufactures). Using a broader definition that includes animals and animal products does not qualitatively change the picture.

trade close to zero goes from the Arctic Circle (66th parallel) to the pole: in that region specialization continues to be in non-agricultural activities, but because of very low population density, the volume of trade is close to zero. To see this, we compute net agricultural exports as a share of GDP by latitude by dividing total net agricultural exports within a latitudinal band by total GDP within that same latitudinal band.¹⁶ Figure 4 clearly shows an area of agriculture at intermediate latitudes, an area of manufacturing at higher latitudes, and a less pronounced area of specialization at equatorial latitudes.

In our benchmark calibration the initial distribution of agricultural and manufacturing TFP as a function of latitude, $Z_M(\ell, 0)$ and $Z_A(\ell, 0)$, will match the two main areas of specialization, an agricultural area at lower latitudes and a manufacturing area at higher latitudes. As for the equatorial region, which in the data shows a weak tendency toward manufacturing specialization, it will arise as a third area in our numerical experiments as the world's temperature increases and agricultural productivity declines at the Equator.

Figure 4. Net Agricultural Exports (Share of GDP) by Latitude



Innovation costs are set to match output growth in agriculture and manufacturing. Given that in our model population is constant, our focus is on output per capita. Using real GDP and population data from the Penn World Tables (PWT 7.0, 2011), we compute annual growth in real GDP per capita in the world economy from 1950 and 2000 and find a figure of 2%. Of course, the growth rate may be different across agriculture and manufacturing. However, this does not seem to be the case. Using data from Duarte and Restuccia (2010), we compare growth in value added per worker in both sectors in a sample of 30 countries. For the period 1950-2000 we find very similar growth

¹⁶We calculate GDP by latitude in an analogous way as trade by latitude by assigning a country's GDP to the different latitudinal bands proportional to the country's population share living within the different latitudinal bands. Data on GDP are for 2000 and come from the World Bank WDI.

rates in both sectors.¹⁷ We therefore assume the same annual output growth rate of 2% in both sectors when matching the innovation costs.

The evolution of the total stock of pollutants depends on the stock of pollutants in the previous period and on the emissions of the previous period, $P(t + 1) = \varepsilon_1 P(t) + \varepsilon_2 (\bar{E}_A(t) + \bar{E}_M(t))$. Because of the carbon cycle, some of the carbon concentration in the atmosphere moves to the upper ocean, and some of the carbon concentration in the upper ocean moves to the atmosphere. In the absence of new emissions, the estimates of the carbon cycle in the RICE model of Nordhaus (2010) imply a net reduction of carbon in the atmosphere by 0.25% every year. This corresponds to a value for ε_1 equal to 0.9975. As for the emissions intensity parameter, ε_2 , it is set to match the predicted increase in carbon in the atmosphere by 800 gigatons of carbon (GTC) by 2100 (Nordhaus, 2010). This yields a value of $\varepsilon_2 = 0.00000137$.¹⁸

The Earth's temperature obviously declines from the Equator to the poles, but the difference is expected to become smaller as a result of global warming. The parameters in the temperature function, $T(\ell, t) = T(\ell, 0) + \nu_1 P(t)^{\nu_2} (1 - \nu_3 T(\ell, 0))$, are calibrated to match the difference in temperatures between the Equator and the North Pole as a function of different levels of pollution. In particular, for $P = 0$ we set the temperature at the Equator to 28 degrees, corresponding to the average temperature in Singapore during the growing season (May-September), and in the North Pole at 0 degrees, corresponding to the average temperature in Dikson (Russia) during the growing season (May-September). Note that we focus on the growing seasons, since they are the relevant ones for the agricultural production function.¹⁹ Predictions are that by 2100 the stock of carbon will increase by 800 GTC and that the temperature at the Equator will increase by around 2 degrees and at the North Pole by around 6 degrees (IPCC, 2007).²⁰ We use these predictions, in addition to the current temperatures by latitude, to calibrate our temperature function. Obviously, many different scenarios exist about the future warming of the planet. The numerical exercises will explore some of these different scenarios.²¹

In the model we keep the world population constant at 7 billion. Clearly, climate change will depend on the evolution of the world population. However, given that there may be important feedback mechanisms between climate change and population growth, we abstract from these changes and leave this issue for future research.

¹⁷In particular, we find a growth rate of 4% in agricultural productivity and of 4.2% in manufacturing. These numbers are substantially higher than the 2% growth in real output per capita in the world economy. The difference may be partly due to the much smaller sample in Duarte and Restuccia (2010), who do not have data on, for example, any African country. From Duarte and Restuccia (2010) we therefore simply conclude that productivity growth rates are similar in both sectors.

¹⁸Note that a gigaton of carbon is equivalent to 3.667 gigatons of CO₂.

¹⁹Clearly, when considering the effect of temperature on manufacturing productivity, there is no reason to focus on the growing season. However, since the temperature-productivity relationship in manufacturing has been calibrated to match the lower share of population living at arctic latitudes, assuming different initial temperatures would simply lead to a different calibration of that relationship, without affecting the results.

²⁰Note that the IPCC predicts a much lower increase at the South Pole than at the North Pole, of 2.75 degrees, rather than of 6 degrees. However, since only 13% of the world's population lives in the Southern Hemisphere, our baseline calibration will focus on the temperature changes in the Northern Hemisphere.

²¹Throughout we report and discuss values of ν_1 that have been divided by $1000/(\pi/2)$ since in all numerical simulations we divide space in 1000 intervals of latitudes between 0 and $\pi/2$. This yields $\nu_1 = 0.0003394$ which we round to $\nu_1 = 0.0003$.

4. BENCHMARK SCENARIOS AND THE EFFECT OF TEMPERATURE

The numerical examples we present compute an equilibrium for 200 years. In this section we focus on explaining the basic forces at work in the model. We will consider different scenarios of temperature increases and will therefore do a number of counterfactual exercises modifying the value of ν_1 , the parameter in equation (5) that determines the relation between the stock of pollutants and temperature. Our benchmark exercise assumes $\nu_1 = 0.0003$, which implies an increase in temperature after 100 years of about 2 degrees at the Equator and 6 degrees at the poles. Throughout this section we assume free mobility of people across locations.

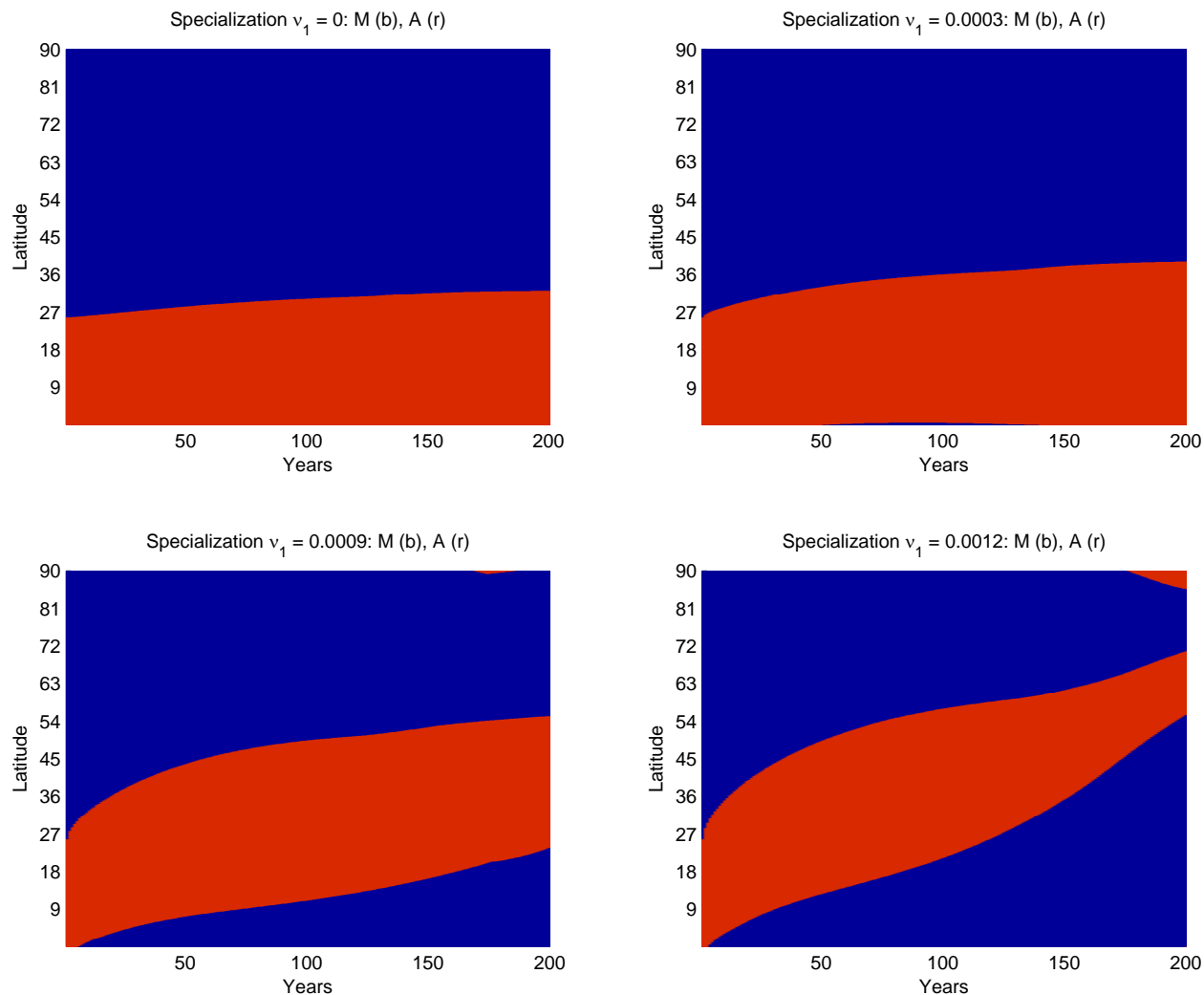
We choose initial productivity functions $Z_M(\ell, t) = 0.8 + 0.4\ell/90$ and $Z_A(\ell, t) = 1.2 - 0.4\ell/90$, so that locations close to the Equator have a comparative advantage in agriculture and locations close to the North Pole have a comparative advantage in manufacturing. These initial productivity functions, together with the relation between temperature and productivity, $g_A(\cdot)$ and $g_M(\cdot)$, determine the specialization pattern across the globe, as illustrated in the top-right panel of Figure 5. The horizontal axis represents time (200 years, going from 2000 to 2200), and the vertical axis represents latitudes in degrees (going from the Equator, at 0 degrees, to the pole, at 90 degrees). The red areas specialize in agriculture and the blue ones in manufacturing.

Over time, as the stock of pollution grows and temperature in the world increases, northern latitudes gain in terms of agricultural productivity, relative to equatorial latitudes, making the region that specializes in agriculture gradually expand northward. As shown by the green curve in Figure 6, initially this leads to a higher manufacturing price, which is eventually counterbalanced by increasing relative productivity growth in manufacturing. The increase in pollution and temperature is shown in Figures 7 and 8. Once again, the benchmark case is represented by the green curves. As can be seen, the stock of pollution increases by 800 GTC in the first 100 years and reaches more than 2000 GTC after 200 years. The increase in temperature by the year 2200 is about 4 degrees at the Equator and more than 8 degrees at the pole.

These changes are accompanied by an important redistribution of people across latitudes. The black-dotted and green lines in Figure 9 present the distribution of population (or employment) by latitudes in the initial year, as well as 100 and 200 years later, respectively. The initial hump shape matches the observed distribution in Figure 1. Over time there is a tremendous increase in population concentration. The world forms two clusters, one in the south, around the 30th parallel, specialized in agriculture, and one in the north, around the 50th parallel, specialized in manufacturing. The Equator and the North Pole are essentially empty, as they are either too warm or too cold to produce efficiently. The concentration of population is the result of free mobility and scale effects in technological innovation. The location of the clusters at intermediate latitudes has to do with their higher productivity because of mild temperatures. Over time, these different forces interact, creating large clusters of population.

The role of innovation in the emergence of clusters of specialization requires some further discussion. In our model geographical concentration of population enhances productivity because the incentives for local innovation are greater when it benefits more people. The higher productivity in turn attracts more people, implying a circular causality that leads to the concentration of economic

Figure 5. Specialization for Different Values of ν_1



activity. This process is weakened by congestion coming from the decreasing returns in output per unit of land ($1 - \mu_i - \sigma_i > 0$ all i). Still, in spite of the relatively large share of land, around one third in both sectors, the decreasing returns are not strong enough to stem the emergence of dense areas of specialization. These clusters are highly innovative, sustaining the rate of output growth of 2% to which we calibrate. The evolution of TFP in both sectors is represented by the green curves in Figure 10. Clearly productivity growth continues unabated even after factoring in the negative effect of temperature. Productivity in both sectors grows almost at exactly the same rate. As a result, the employment share in agriculture stays essentially constant over time, as does its area of specialization. We present the agricultural employment share in Figure 11.

The resulting equilibrium increases current utility throughout the 200 years under study, as illustrated by the green curve in Figure 12. Remember that all agents obtain identical utility given free mobility and uniform ownership of land. Hence, in our calibrated exercise, the effect of innovation dominates the effect of temperature: A direct implication of our choice to calibrate the

Figure 6. Relative Price for Different Values of ν_1

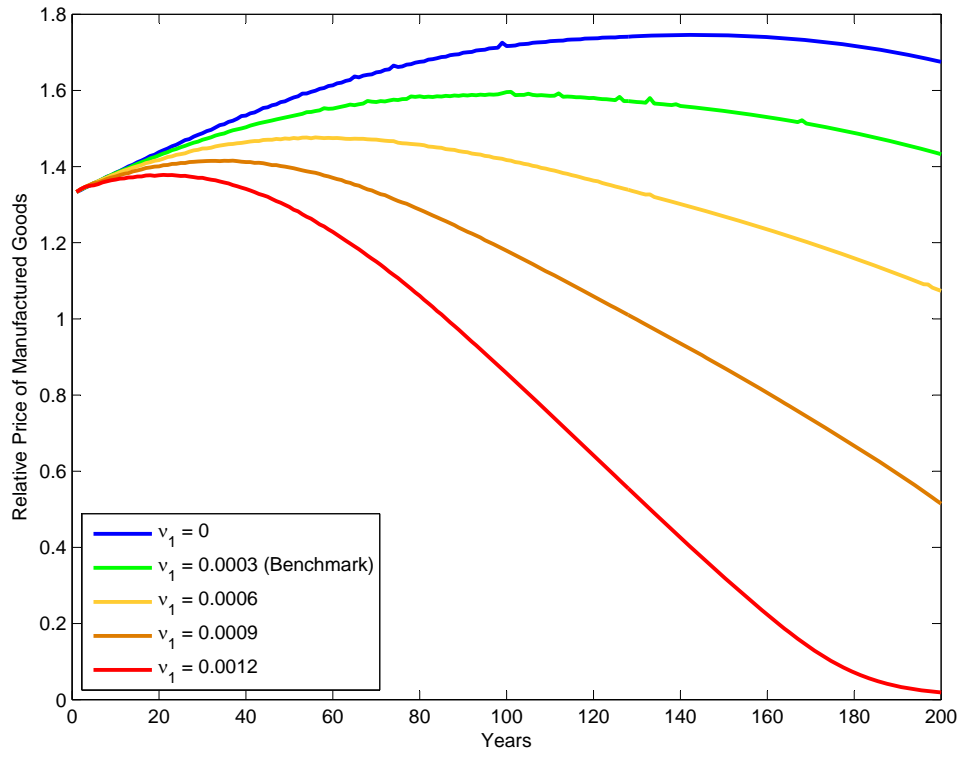


Figure 7. Pollution for Different Values of ν_1

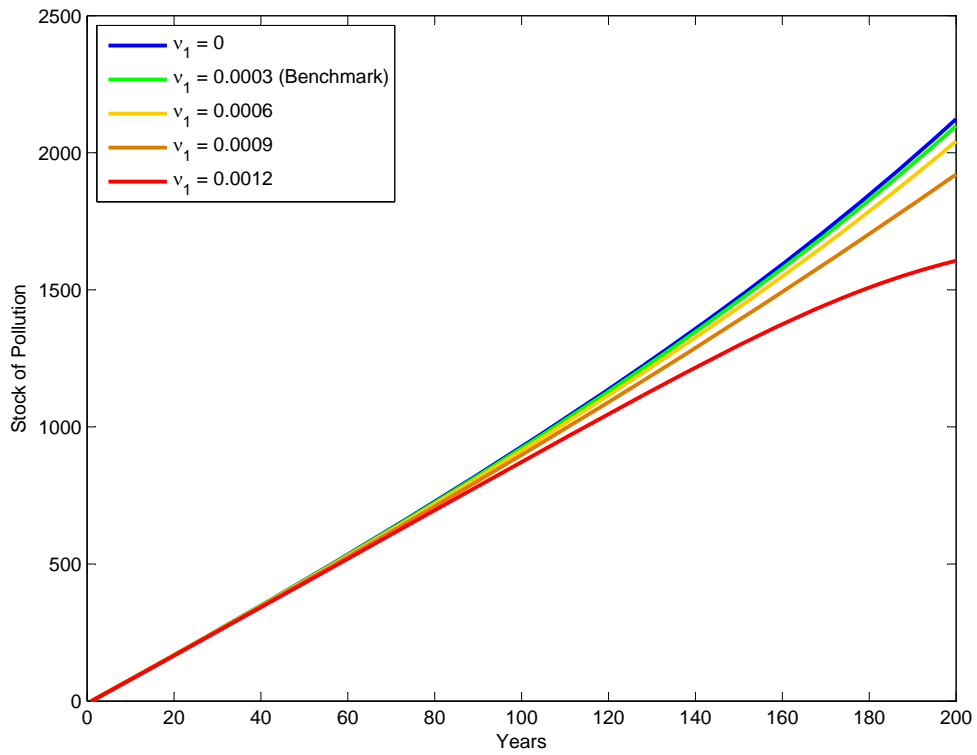


Figure 8. Temperature for Different Values of ν_1

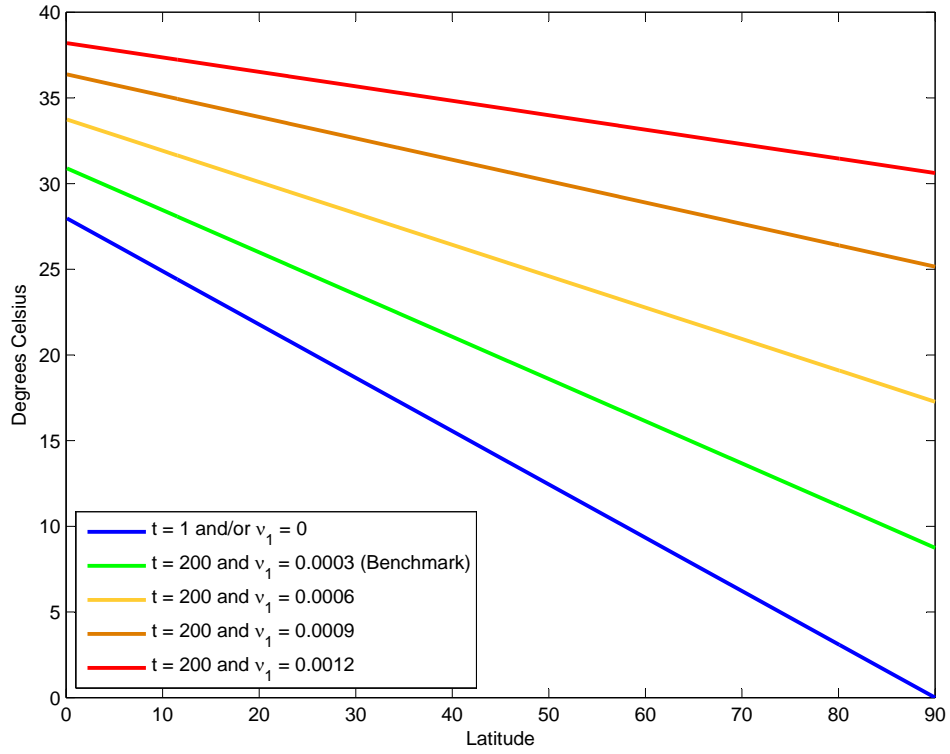


Figure 9. Population Shares for Different Values of ν_1

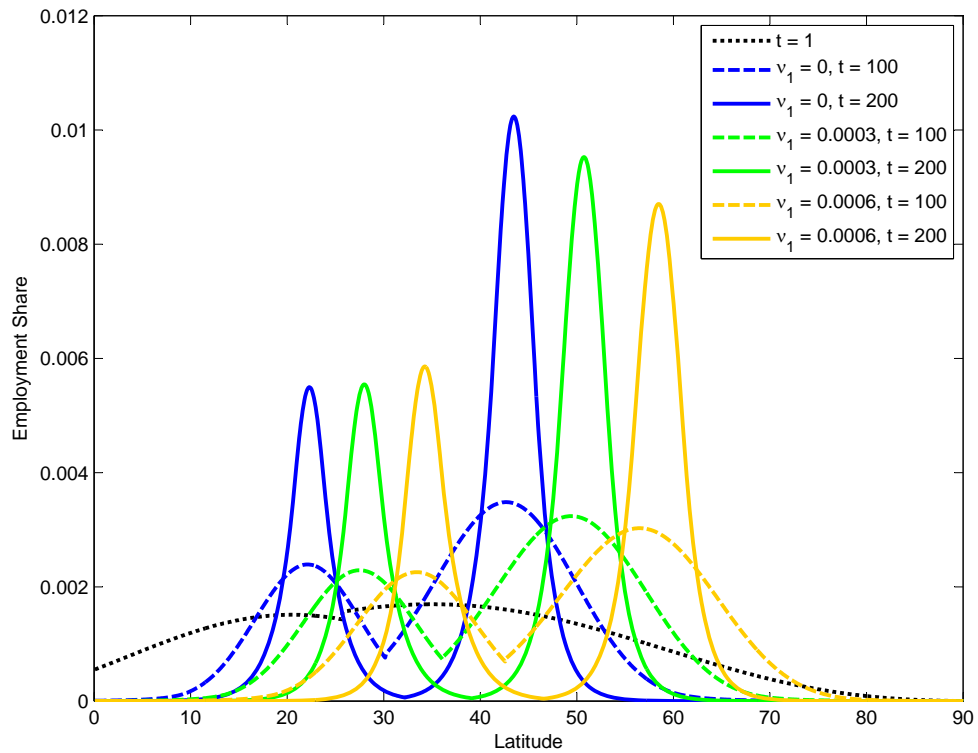
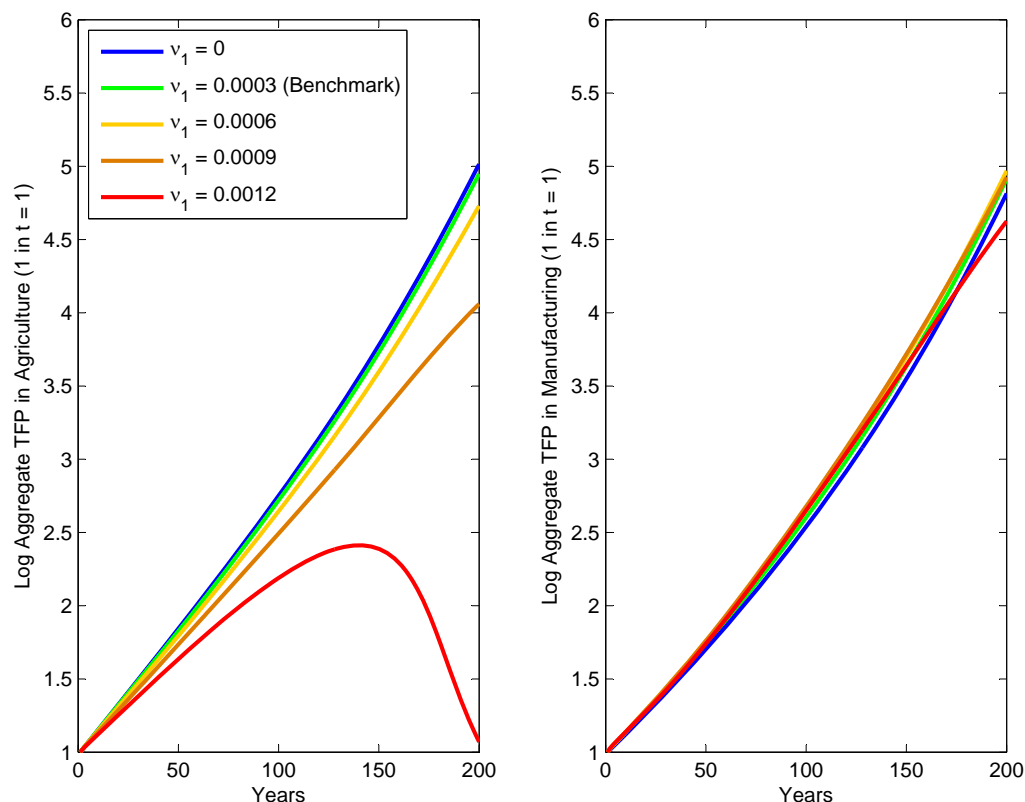


Figure 10. Aggregate TFP for Different Values of ν_1



innovation parameters to obtain a per capita income growth of 2% per year. Still, if we were to abstract from the effect of temperature on productivity ($\nu_1 = 0$) to do the calibration, the effect would be very similar, since for levels of ν_1 between 0 and the calibrated value of 0.0003, the effect of ν_1 on output per capita growth is minimal. Global warming has important implications for the spatial pattern of specialization but a relatively small effect on utility unless we go to extreme scenarios, as discussed below. The economy adjusts in an efficient way to accommodate global warming. Of course, in this paper we exclusively focus on the effect of temperature on productivity and leave aside other reasons why temperature or location could lead to lower levels of well-being.²²

The benchmark equilibrium described above considers a moderate scenario for the effect of pollution on temperature. This effect is governed by our choice of 0.0003 for the parameter ν_1 in equation (5). Figures 5 to 12 present equilibria using alternative values of ν_1 , ranging from 0 (no effect of temperature on productivity) to 0.0012 (extreme effect of pollution on temperature). As mentioned before, the calibrated value of $\nu_1 = 0.0003$ corresponds to estimates of what the increase in temperature will be by 2100. The effect of this parameter can be most easily appreciated in Figure 8. The benchmark value of $\nu_1 = 0.0003$ implies that temperature increases at the North Pole by 8 degrees over a period of 200 years, whereas the extreme scenario of $\nu_1 = 0.012$ would imply a

²²For example, the lesser hours of sunlight in more northern latitudes may have a direct negative effect on people's utility. For evidence on the effect of climate on utility, see Graff Zivin and Neidell (2013) and Albouy et al. (2013).

Figure 11. Sectoral Employment Shares for Different Values of ν_1

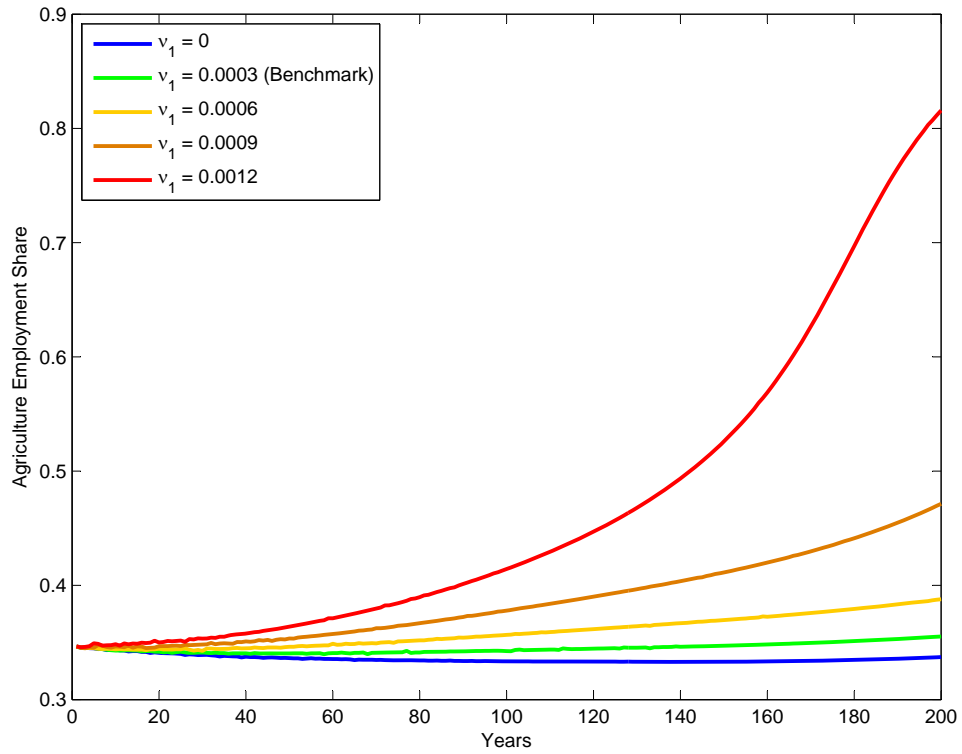
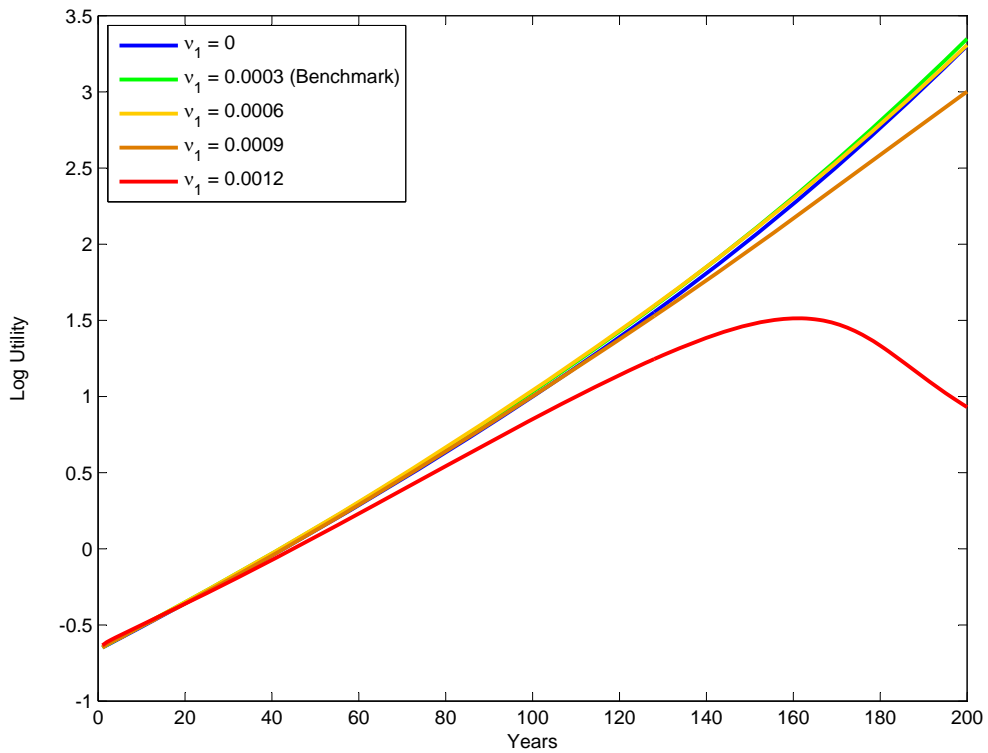


Figure 12. Utility for Different Values of ν_1



corresponding increase of 30 degrees. While unlikely to occur, these extreme counterfactuals help to illustrate the effect temperature has in our model.

As already mentioned, when comparing the benchmark case ($\nu_1 = 0.0003$) to the case in which we ignore the effect of temperature on productivity ($\nu_1 = 0$), global warming seems to have a limited effect. The most relevant difference relates to where the two clusters of specialization emerge. As can be seen from comparing the green curves to the blue curves in Figure 9, the two clusters of specialization emerge about 10 degrees more north when taking into account the effect of temperature ($\nu_1 = 0.0003$) compared to when temperature has no effect ($\nu_1 = 0$). Further increasing ν_1 to 0.0006 enhances the effect of pollution on temperature, pushing both clusters even further north. Similarly, Figure 5 shows that the greater ν_1 , the more agriculture moves to northern latitudes. As the effect of temperature on productivity increases and the ideal location to produce agriculture shifts north, the comparative advantage of the south changes. The equatorial regions become too warm for agriculture and start specializing in manufacturing. But this does not give rise to the emergence of a new high-density manufacturing cluster, as few people end up living in these equatorial latitudes. As can be seen from Figure 9, the spatial distribution continues to be characterized by two clusters, one in agriculture and another in manufacturing. Higher values of ν_1 increase the size of the agricultural cluster and decrease the size of the manufacturing cluster. This happens because higher values of ν_1 imply a bigger rise in temperature and thus a greater dampening of productivity growth in agriculture (Figure 10). Given an elasticity of substitution between agriculture and manufacturing of less than one, this leads to a larger increase in the agricultural employment share (Figure 11) and a drop in the relative price of manufacturing (Figure 6).

Except for the extreme temperature scenario ($\nu_1 = 0.0012$), the effect of global warming on utility is limited (Figure 12). Furthermore, the effect need not be monotone: starting off with no change in temperature ($\nu_1 = 0$), increasing global warming initially raises utility ($\nu_1 = 0.0003$) but then lowers it (for values of ν_1 greater than 0.0006). This illustrates that, depending on a location's initial temperature, global warming may increase or decrease its productivity. For moderate levels of global warming, the higher productivity in northern regions more than compensates the lower productivity in equatorial regions, and welfare improves. For higher temperature increases, the losses in equatorial latitudes start to dominate, and welfare decreases.

Figures 5 and 9 help us better understand why the effect of global warming on productivity and utility is generally limited. The increase in temperature relocates economic activity and people across latitudes. Essentially, the level of temperatures determines whether the manufacturing cluster will be at the 40th parallel, the 50th parallel, or the 60th parallel. Within the range of expected temperature increases over the next two centuries, the world has enough flexibility to limit the overall effect of climate change by relocating production and people. This finding is subject to a number of important caveats. First, in our model the world population does not increase. If the overall world population were to grow, then the possibility of fitting a greater share of the world population in the most desirable latitudes would be more limited. Second, we are ignoring any costs related to the relocation of people and activities. These costs may be related to, amongst others, policy frictions, increased inter-group violence, and the loss of physical capital in locations

negatively impacted by climate change. In the next section we will analyze the impact of mobility restrictions. Third, while in the next 200 years the effect of global warming may be limited, in the very long run it will lead to disaster. As the world continues to warm, agricultural production will be shifting further north, eventually reaching the North Pole. At that point it can no longer adjust by relocating. Further temperature increases will then lead to agricultural productivity going to zero, implying the end of human life on earth. Although our analysis has focused on only 200 years, we get a flavor of this disastrous outcome when setting ν_1 to the extremely high value of 0.0012. In that case agricultural productivity would start declining, as innovation no longer compensates the negative impact of temperature increase (Figure 11). Likewise, utility would stop increasing and start going down (Figure 12).

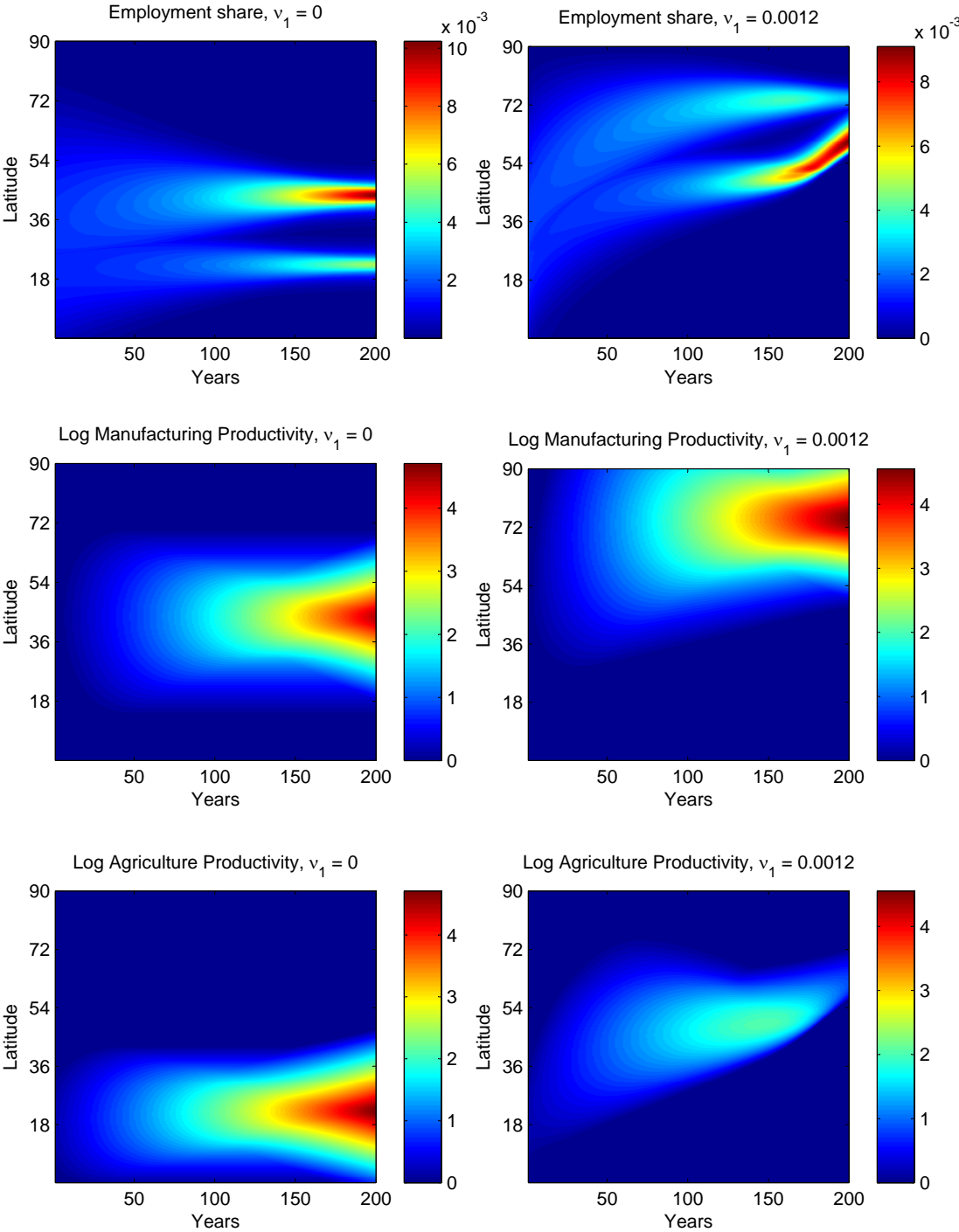
To summarize the effect of global warming on the equilibrium of our model, we present in Figure 13 a comparison between the case of no effect of pollution on temperature ($\nu_1 = 0$) and the case of extreme effects of pollution on temperature ($\nu_1 = 0.0012$). The figure shows contour plots of employment shares (first row), manufacturing productivity (second row) and agriculture productivity (third row). The left column presents the equilibrium with $\nu_1 = 0$ and the right one with $\nu_1 = 0.0012$.

Focus first on the effect of temperature increases on the location of the world's employment clusters (first row). When pollution has no effect on temperature, two clusters emerge, one specializing in agriculture around the 20th parallel and a second specializing in manufacturing around the 45th parallel. In contrast, when $\nu_1 = 0.0012$, the formation of the employment clusters changes dramatically. Now the largest cluster is in agriculture, and it progressively moves north as temperature continues to rise. The manufacturing cluster still forms, but it is also pushed northward, and becomes less dense. This happens partly because the equatorial regions start producing more manufactured goods (Figure 5) and partly because the drop in agricultural productivity implies that a larger share of the population is employed in agriculture (Figure 11).

The effect of global warming on productivity differs dramatically across sectors (Figure 13, second and third row). In manufacturing, higher temperatures do not seem to have a negative impact on manufacturing productivity growth; it simply moves innovation further north. In equatorial regions, in spite of switching to manufacturing, there is no productivity increase. Rising temperatures and a lack of innovation keep the south's manufacturing technology backward. In agriculture, rising temperatures have a more dramatic effect. They initially lead to an increase in productivity, but eventually the negative impact of global warming dominates the investments in innovation, and overall productivity declines. As a result, the employment share in agriculture shoots up to more than 80% by the end of the 200-year period.

The comparisons in Figure 13 show the delicate balance between migration, technological innovation, and the effect of temperature. They illustrate an extreme comparison. While the actual calibrated effect of global warming is much smaller, the direction of the change is similar. The agricultural cluster shifts north, without the manufacturing cluster moving south because of the north's accumulated technological advantage in that sector. At the same time, productivity growth in agriculture becomes relatively harder, as it suffers more from temperature increases than manufacturing.

Figure 13. Contour Plots of Employment Shares and Productivity ($\nu_1 = 0$ and $\nu_1 = 0.0012$)



As we argued above, a key reason why the economy responds well to global warming in the calibrated version of the model has to do with the free mobility of people and goods. If these flows of people and goods were not possible or were restricted, the effects of global warming are likely to change. In the next section we explore the impact of such restrictions.

5. MIGRATION AND TRADE RESTRICTIONS

We now analyze how migration restrictions affect the economic impact of global warming. Quantifying these costs is complex. The ease of moving people or activities is partly related to policy choices. Climate policy, migration policy and trade policy are therefore related. But there are other costs that go beyond policy. Climate refugees may increase the likelihood of war and inter-group violence. The cost of migration will also include the impossibility of moving some of the physical capital and infrastructure. Since a careful calibration of these costs goes beyond the scope of this paper, in this section we will focus on two specific cases. A first exercise aims to capture the tensions that are likely to arise between north and south by introducing an insurmountable border between southern and northern latitudes. A second exercise aims to provide an upper-bound on the possible losses from global warming by assuming everyone is stuck and no one can migrate.

We start by setting a border between the north and the south at the 45th parallel. In 2000 around 90% of the world population lived between the Equator and the 45th parallel (adding both hemispheres). We therefore split the world population of 7 billion and allocate 6 billion to the south (the region between the Equator and the 45th parallel) and 1 billion to the north (the region between the 45th parallel and the pole). We allow people to move freely within each region but not across regions. This implies that all agents in the south have the same utility, as do all agents in the north, but southern and northern agents will have different utility levels.²³

In Table 2 we present the value of consumer welfare (the maximum value of the objective in (1)) for a discount factor of $\beta = 0.95$.²⁴ The top panel reports welfare in the case of free mobility for different values of ν_1 . This corresponds to the exercise in the previous section. The middle panel reports welfare when we impose migration restrictions. It distinguishes between welfare in the north, welfare in the south, average welfare, and relative welfare. It also computes percentage changes and differences, relative to the case where pollution has no effect on temperature ($\nu_1 = 0$). The bottom panel reports the same information but adds a 20% trade barrier between north and south.

Migration restrictions benefit the north, and more so when the effect of pollution on temperature is large. The reason is straightforward. As temperature rises, the north becomes a relatively better place to produce. When there is free mobility, this attracts southern migrants, and wages drop.

²³In order not to affect credit markets as well, we maintain the assumption that all agents in the world hold a diversified portfolio of the same size of all land in the world. Of course, in the presence of migration restrictions if we were to allow agents to choose their portfolio optimally, they might decide to trade some of it.

²⁴Note that the value of β did not play a role before, since all decisions of firms and agents end up being static. However, the value of β is essential in determining the value of consumer welfare. Many of the studies on climate change choose somewhat higher discount factors. Nordhaus (2010) and Golosov et al. (2011), for example, use a discount factor of 0.985, whereas Stern (2006) uses an even higher 0.999. We assess below the sensitivity of our results to higher discount factors.

Table 2. Welfare at $t = 0$ with Migration and Trade Restrictions Using $\beta = 0.95$

		ν_1			
		0	0.0003	0.0006	0.0009
Free Mobility	All	0.7179	0.7247	0.7259	0.7176
	% Δ		0.0095	0.0111	-0.0005
Migration Restriction at 45° ($\bar{L}_S/\bar{L}_N = 6$)	North	0.7908	0.8258	0.8531	0.8592
	% Δ		0.0443	0.0787	0.0865
	South	0.7162	0.7162	0.7061	0.6799
	% Δ		-0.0001	-0.0141	-0.0507
	Average	0.7269	0.7318	0.7271	0.7055
	% Δ		0.0068	0.0003	-0.0294
	Relative S/N Ratio	0.9057	0.8672	0.8277	0.7913
	Δ		-0.0385	-0.0780	-0.1144
Migration Restriction + Trade Barrier of 20% at 45° ($\bar{L}_S/\bar{L}_N = 6$)	North	0.7800	0.8120	0.8363	0.8387
	% Δ		0.0411	0.0722	0.0753
	South	0.7105	0.7100	0.6998	0.6721
	% Δ		-0.0006	-0.0150	-0.0541
	Average	0.7204	0.7246	0.7193	0.6959
	% Δ		0.0058	-0.0015	-0.0341
	Relative S/N Ratio	0.9109	0.8744	0.8368	0.8013
	Δ		-0.0365	-0.0741	-0.1096

$\beta = 0.95$. All % Δ are relative to the same exercise with $\nu_1 = 0$.

Now no migrants from the south can enter, and so agents in the north maintain their higher wages. In contrast, agents in the south lose from global warming. The loss is minimal when ν_1 is small, but the effect grows as ν_1 increases. There are two countervailing effects. On the one hand, by not allowing migration, the concentration of people in the south is larger, making them innovate more. This leads to faster growth and higher welfare for southern agents. On the other hand, agents cannot move out of the south, resulting in welfare losses.²⁵ When pollution has no effect on temperature ($\nu_1 = 0$), both effects balance out, making the migration restrictions almost welfare neutral (a 0.24% decline in welfare or in aggregate consumption given that utility is linear). The total effect could very well have been positive. Because diffusion is an externality, the equilibrium in this economy is not Pareto optimal, and so migration restrictions could potentially enhance welfare. When we increase ν_1 and the effect of pollution on temperature becomes larger, the negative effects of global warming in the south start dominating the positive agglomeration effects. For example, in the case of $\nu_1 = 0.0009$, southern agents obtain 5% lower welfare than if pollution and temperature were unrelated, and 5.2% less welfare than in the case of free mobility.

The implication of Table 2 is that global warming amplifies inequality between northern and southern agents when there are migration restrictions. Relative welfare goes from 90% when $\nu_1 = 0$ to 79% when $\nu_1 = 0.0009$. Migration restrictions also amplify the overall effect of global warming on welfare by hindering the natural adjustment of specialization and migration patterns. For example, when increasing ν_1 from 0.0006 to 0.0009, average welfare decreases by around 3% when there

²⁵The border introduces an initial welfare difference in period 1 of 20% in favor of the north.

are mobility restrictions, whereas it remains essentially unchanged when there is free mobility. This implies that in the benchmark case of the previous section, it was mobility that prevented global warming from having important welfare effects. In this sense global warming and mobility restrictions complement each other, leading to larger negative effects from pollution.

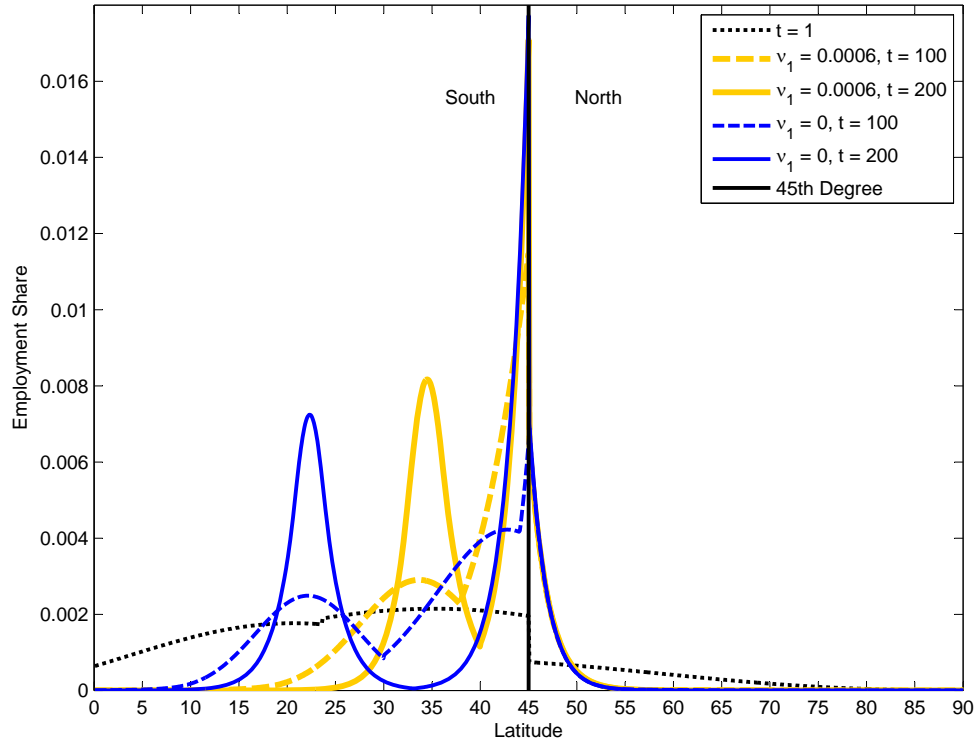
To see how migration restrictions change the clustering of people, compare Figure 14, which shows employment shares at each of the 1000 locations in our grid, and Figure 9, which shows the same information for the case of free mobility. Recall that the migration restriction is imposed at the 45th parallel, which is marked with a vertical line in the graph. The black dotted line indicates employment shares in period 1, common to all values of ν_1 . The figure also reports employment shares for $\nu_1 = 0$ and $\nu_1 = 0.0006$, 100 and 200 years later. Over time employment concentrates in two clusters. In the absence of any effect of pollution on temperature ($\nu_1 = 0$), the clusters locate around the 20th parallel and the 45th parallel, similar to the case of free mobility in Figure 9. When ν_1 increases to 0.0006, the higher temperature in the south pushes the agricultural cluster to the 35th parallel, but the manufacturing cluster remains stuck at the border. This stands in sharp contrast to the case of free mobility in Figure 9, where for the same value of ν_1 manufacturing had moved much further north, close to the 60th parallel. In other words, because of the mobility restrictions, the manufacturing cluster remains stuck at the border, and global warming has no impact on the cluster's location. This is especially striking in the north, where there is no perceptible difference in the distribution of population after 100 years and after 200 years. Although technology continues to change (as do prices, etc.), for all practical purposes people in the north stop moving. The north gains from global warming because its trade partners move closer (the two clusters move closer together) and because technology to produce in the north is now better due to the increase in temperature. The south also gains from the trade effect but loses due to the negative effect of global warming on its productivity.

The apparent importance of these trade effects suggests that trade frictions at the border might also interact in relevant ways with the effect of pollution. The bottom panel in Table 2 presents another exercise where, on top of migration restrictions, we impose a trade barrier of 20% at the border. This barrier leads to a discontinuous increase in the price of the good that is crossing the border.²⁶ Furthermore, it is of the iceberg type and involves a real cost in terms of resources. Not surprisingly, the trade barrier reduces welfare both in the north and in the south for all values of ν_1 . However, since the effects of global warming on northern welfare rely heavily on the fact that the southern clusters move closer to the northern border and the resulting increase in trade, the north suffers more from the new trade friction. The relative well-being in the south still deteriorates with global warming but less than before. That is, the south loses more than before from global warming, but it is less worse off *relative* to the north.

The exercise with migration restrictions as well as trade frictions at the border illustrates how trade policy can ameliorate some of the redistributive effects of global warming across the north and south but only at the cost of making everyone worse off. This effect would be mitigated if

²⁶Note the difference between the transport costs governed by κ and this barrier. One applies continuously in space since it is costly to transport goods across any two locations. The other applies only at the border and so it is a cost of exporting goods. In setups without space these two costs are indistinguishable.

Figure 14. Population Shares for Different Values of ν_1 and Migration Restrictions



the trade barrier did not involve an actual loss in resources. In that case the tariff would make southerners better off for low values of ν_1 , even though the loss of northern welfare would still imply a loss in average welfare.

We have set the border arbitrarily at the 45th parallel. The importance of migration and trade frictions depends on the location of this border and, in particular, on the location of this border relative to the two large population clusters. To check the robustness of our results to the location of the border we calculate the same exercises with the border at the 40th and 60th parallels (we attribute population proportionally across countries in the segment that is added to the north or south respectively). The results are qualitatively the same. In particular, global warming has larger welfare costs in the presence of migration restrictions and the larger the effect of carbon on temperature, the larger the impact of migration restrictions.²⁷ These additional results also uncover a new pattern. Namely, the more to the north the border, the smaller the overall costs of global warming. For example, with $\nu_1 = 0.0006$, the average welfare gain/loss relative to the case with $\nu_1 = 0.0003$ is 0.3% with the border at 60°, -0.6% with the border at 45° and -1.1% with the border at 40°. Of course, if we go to $\nu_1 = 0.0009$ even with the border at 60° latitude we get a welfare loss of -1.1%. A border further north benefits a few northerners, but also allows southern agents to cluster in parallels with cooler temperatures in higher latitudes (and so southern utility relative to northern utility grows).

²⁷In fact, average welfare seems to peak with a border close to intermediate latitudes, with average welfare going from 0.731 to 0.732 and then to 0.727 as we change the border from latitude 40° to 45° and to 60°, respectively.

In the welfare comparison in Table 2 we use a value of β equal to 0.95. Given that this economy exhibits growth over time and many of the effects we have discussed are dynamic, the magnitude of the temporal discount is important. For example, the positive growth effect generated by the concentration of people in the south that we highlighted above plays a larger role in welfare when the discount factor is closer to one and so agents discount the future less. To show this, in Table 3 we redo the welfare calculations using a value of β of 0.98. The positive agglomeration effect of the migration restriction now dominates the negative effect of global warming on the south and so both the northern and southern agents gain from the migration restrictions. In other words, even though southern agents would have a static incentive to move to the north, it would be better for them to stay put. All other relative comparisons between north and south remain unchanged though. The south still loses from global warming relative to the north, and the effect is weaker in the presence of trade barriers. As we discussed in the previous section, global warming can be welfare increasing for low values of ν_1 . This is the case for values of $\nu_1 = 0.0003$ in Table 2 and for values of ν_1 up to 0.0006 in Table 3. However, once ν_1 is high enough so that global warming is welfare decreasing, the presence of migration frictions again amplifies the effect of global warming. For example, if $\nu_1 = 0.0009$ rather than 0.0006, welfare with labor mobility declines by 7.0% but it declines by 9.3% with migration restrictions.

Table 3. Welfare at $t = 0$ with Migration and Trade Restrictions Using $\beta = 0.98$

		ν_1			
		0	0.0003	0.0006	0.0009
Free Mobility	All	1.6096	1.6522	1.6449	1.5295
	% Δ		0.0265	0.0219	-0.0498
Migration Restriction at 45° ($\bar{L}_S/\bar{L}_N = 6$)	North	2.1792	2.3743	2.6274	2.5126
	% Δ		0.0895	0.2057	0.1530
	South	1.9530	2.0711	2.1811	1.9555
	% Δ		0.0605	0.1168	0.0013
	Average	1.9853	2.1144	2.2448	2.0351
	% Δ		0.0650	0.1307	0.0251
	Relative S/N	Ratio	0.8962	0.8723	0.8301
	Δ		-0.0239	-0.0422	-0.0518
Migration Restriction + Trade Barrier of 20% at 45° ($\bar{L}_S/\bar{L}_N = 6$)	North	2.1323	2.3161	2.5500	2.4179
	% Δ		0.0862	0.1959	0.1340
	South	1.9301	2.0466	2.1551	1.9274
	% Δ		0.0603	0.1166	-0.0014
	Average	1.9590	2.0851	2.2115	1.9974
	% Δ		0.0644	0.1289	0.0196
	Relative S/N	Ratio	0.9052	0.8836	0.8451
	Δ		-0.0216	-0.0601	-0.1081

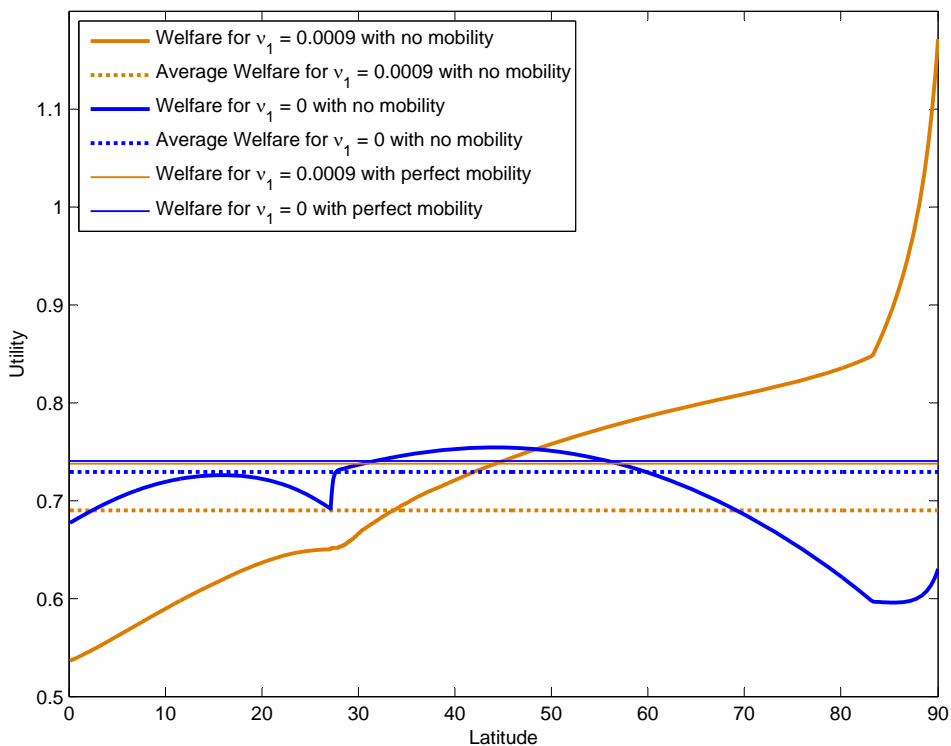
$\beta = 0.98$. All % Δ are relative to the same exercise with $\nu_1 = 0$.

To further illustrate how mobility frictions amplify the impact of global warming, we now compare the two extreme cases of free migration across all locations and no migration across any location. While assuming that people cannot move at all, not even locally, over a period of two centuries

is admittedly unrealistic, it serves the purpose of highlighting that the economic cost of climate change is mainly due to mobility frictions. To make the comparison between both extremes as sharp as possible, we exclusively focus on migration frictions, and therefore set transportation costs to zero. In the no migration case we start the economy with the distribution of people across locations from the first period of the equilibrium with free migration, and do not let anyone move over the 200 years of the analysis.²⁸ This will obviously lead to utility differences across locations. To make welfare comparisons with the perfect mobility case, we take the utilitarian view, and compute the population-weighted average utility across all locations.

Figure 15 shows the discounted sum of utility across different latitudes, comparing the no migration case with the free migration case under two scenarios: no change in temperature ($\nu_1 = 0$) and extreme change in temperature ($\nu_1 = 0.0009$). When there is free mobility, the difference between the two solid lines indicates that climate change lowers welfare (or consumption) by 0.38%. The same comparison when there is no mobility, given by the difference between the two dashed lines, reveals a welfare cost of 5.38%, more than an order of magnitude larger than in the free mobility case. Hence, in the absence of migration restrictions global warming essentially has no impact, but when people are unable to move the effect is substantial.

Figure 15. Utility under Free Migration and No Migration



So far we have assessed the welfare cost of no migration focusing on population-weighted averages. The impact of the lack of mobility is even more dramatic when we look at welfare differences across

²⁸We smooth out the distribution using a Hodrick-Prescott filter with parameter 1000000 to avoid kinks (we use a grid of 1000 points), facilitate computations, and bring the distribution closer to the empirical distribution.

latitudes. This is represented by the two thick solid curves in Figure 15. In the absence of climate change, intermediate latitudes, between the 30th and 60th parallels, gain relative to the case with mobility, whereas equatorial and polar latitudes lose. The welfare difference between winners and losers is around 20%. In the presence of climate change, these differences are hugely amplified, with welfare in the polar regions being more than twice that of equatorial regions.²⁹ In most latitudes the impact of global warming depends crucially on whether people can move or not. However, this is not the case for intermediate latitudes: locations around the 45th parallel are hardly affected by global warming, independently of whether we allow for migration or not. The 45th parallel passes through the Northern United States, Southern France, Northern Italy, Northern China and Northern Japan. The model suggests that those regions of the world should be largely indifferent to the effects of climate change. This also implies that global warming will lead to increased migratory pressure from the regions below the 45th parallel north to those above the 45th parallel north. This explains our choice of setting the border at that particular latitude in our initial exercise on migration restrictions.

6. ENERGY TAXES AND INNOVATION SUBSIDIES

In this section we explore the impact of energy taxes and innovation subsidies and how the effect of these taxes interacts with global warming. The competitive equilibrium of our economy is not Pareto efficient due to two distinct externalities. First, technology diffuses across locations, and second, economic activity at one location affects the global stock of pollution and therefore the temperature and the productivity at all locations. So the pollution generated in one location affects the productivity in all other locations. These two externalities imply that a variety of frictions and policies can be welfare improving. This is the case for the two policies we analyze in this section.³⁰

Energy taxes reduce the use of energy and so reduce pollution and global warming. This mechanism is well known and operative in our framework. Table 4 presents welfare and the stocks of carbon (expressed in GTC) after 200 years for different levels of ad-valorem taxes on energy used by firms. The percentage changes presented in the table are all relative to the same economy without the tax. We rebate the tax to all agents equally so the tax has no wealth effects but it generates distortions in input use.

In our model energy use is directly related to pollution and temperature increases. In this sense, what we call energy is best interpreted as carbon-generated energy. Hence an energy tax in our context is equivalent to a tax on carbon emissions and should be interpreted as such. Note that because we are not modeling different forms of energy generation, energy taxes will not lead to substitution between energy sources, nor will they lead to energy-saving technological change. Still, they will lead to Hicks-neutral innovations that will tend to save on all factors, including energy.

As Table 4 indicates, energy taxes are, in general, welfare improving. This is the case even when

²⁹In Figure 15, the kinks in the curves representing welfare for the no mobility case are associated with changes in specialization that are amplified by different innovation rates across industries.

³⁰Note that the structure of our model allows us to compute a competitive equilibrium but not the planner's problem. In the latter case the planner needs to form expectations about the path of the distribution of economic activity across space. This problem is, as far as we know, intractable and makes solving for the optimal policy in our framework infeasible.

$\nu_1 = 0$. The reason is that an energy tax makes high-productivity regions relatively better, leading to more clustering and innovation. This happens because high-productivity locations rely more on technology and less on inputs, so that the impact of an energy tax is relatively smaller. A 100% tax increases welfare by 1.2% when $\nu_1 = 0$, while a 400% tax increases it by 2.9%. Once ν_1 becomes positive and pollution increases temperatures, the effect of the tax is larger, the larger is ν_1 . With $\nu_1 = 0.0012$ a 100% tax increases welfare by 2.0%, while a 400% tax increases it by 5.4%.³¹ The higher ν_1 , the greater the effect of pollution on temperature, and so the reduction in energy use leads to larger welfare gains.³² The amount of energy used decreases with the tax, although the drop is not always increasing in ν_1 .

Table 4. Welfare and carbon Stocks with Different Energy Taxes

Energy Tax		ν_1				
		0	0.0003	0.0006	0.0009	0.0012
0%	Welfare	0.7179	0.7247	0.7259	0.7176	0.6949
	Carbon in $t = 200$	2223	2097	2042	1921	1606
100%	Welfare	0.7268	0.7336	0.7351	0.7279	0.7089
	% Δ	0.0123	0.0122	0.0128	0.0143	0.0202
	Carbon in $t = 200$	1984	1944	1880	1770	1526
	% Δ	-0.1075	-0.0730	-0.0793	-0.0786	-0.0498
200%	Welfare	0.7376	0.7443	0.7466	0.7419	0.7265
	% Δ	0.0273	0.0269	0.0285	0.0339	0.0455
	Carbon in $t = 200$	1690	1674	1640	1572	1419
	% Δ	-0.2398	-0.2017	-0.1969	-0.1817	-0.1164
400%	Welfare	0.7389	0.7454	0.7480	0.7447	0.7324
	% Δ	0.0292	0.0285	0.0305	0.0377	0.0540
	Carbon in $t = 200$	1522	1509	1581	1428	1319
	% Δ	-0.3153	-0.2804	-0.2258	-0.2566	-0.1787
800%	Welfare	0.7375	0.7438	0.7467	0.7445	0.7350
	% Δ	0.0273	0.0263	0.0287	0.0375	0.0578
	Carbon in $t = 200$	1351	1340	1318	1279	1201
	% Δ	-0.3923	-0.3610	-0.3546	-0.3342	-0.2522

$\beta = 0.95$. Carbon stocks in GTC. All % Δ are relative to the case with no energy tax.

Larger taxes on carbon have marginally smaller effects on welfare. The elasticity of welfare with respect to the energy tax is positive but declining in the tax and eventually turns negative. For low values of ν_1 it turns negative for lower taxes than for large values of ν_1 . So larger effects of carbon stocks on temperature justify larger energy taxes. For $\nu_1 = 0.0012$ even a tax of 800% results in a positive elasticity of welfare with respect to the tax. So carbon taxes are clearly beneficial in our setup. They promote growth by reducing carbon emissions. It is important not to overdo

³¹While our results suggest that an energy tax could yield welfare gains of between 3% and 5%, Nordhaus (2010) finds a much lower 0.35%. One reason for the larger effect in our model is the presence of externalities, which imply that energy taxes improve welfare even in the absence of a relation between emissions and temperature.

³²Note that even in the absence of taxes, a higher effect of pollution on temperature leads to a reduction in emissions and so the stock of carbon declines with ν_1 . This effect is mostly the result of the slowdown in economic activity associated with temperature increases.

them when the effect of pollution on temperature is small. However, even in our benchmark case of $\nu_1 = 0.0003$, a 400% tax is justified, although an 800% tax is not.³³

Figure 16 focuses on the extreme temperature scenario ($\nu_1 = 0.0012$) and presents contour plots of employment shares and agricultural productivity for the case of no tax (top panel), a 200% tax (middle panel), and an 800% tax (bottom panel). Recall that when discussing Figure 13 we argued that for the case of $\nu_1 = 0.0012$ global warming eliminates productivity growth in the agricultural sector. As can be seen in the top panel, in the absence of a carbon tax, technology in agriculture regresses. All clusters move far north, and the agricultural cluster becomes much more important than the manufacturing one in terms of population, as the employment share in agriculture skyrockets. Once we introduce energy taxes, these phenomena weaken or are delayed in time. The higher the tax, the less the clusters move north, the larger the manufacturing cluster remains relative to the agricultural one, and the smaller the technological regress in the agricultural sector. In fact, for the 200-year period we examine, the technological regress in agriculture turns to progress when the tax is raised to 800%, an optimal tax in this extreme scenario according to our calculations.

Table 5. Welfare and Average Output Growth with Different Innovation Subsidies

Innovation Subsidy		ν_1				
		0	0.0003	0.0006	0.0009	0.0012
0%	Welfare	0.7179	0.7247	0.7259	0.7176	0.6949
	Avg. $\% \Delta$ in Y_M	0.0196	0.0200	0.0201	0.0193	0.0141
	Avg. $\% \Delta$ in Y_A	0.0203	0.0200	0.0193	0.0165	0.0031
20% both Industries	Welfare	0.7574	0.7649	0.7659	0.7558	0.7286
	$\% \Delta$	0.0549	0.0553	0.0551	0.0532	0.0485
	Avg. $\% \Delta$ in Y_M	0.0215	0.0219	0.0219	0.0210	0.0149
	Avg. $\% \Delta$ in Y_A	0.0222	0.0220	0.0211	0.0179	0.0031
40% both Industries	Welfare	0.8147	0.8232	0.8238	0.8111	0.7766
	$\% \Delta$	0.1348	0.1358	0.1350	0.1303	0.1176
	Avg. $\% \Delta$ in Y_M	0.0239	0.0243	0.0243	0.0230	0.0160
	Avg. $\% \Delta$ in Y_A	0.0246	0.0244	0.0234	0.0196	0.0031

$\beta = 0.95$. All $\% \Delta$ are relative to the case with no innovation subsidies.

We now turn to studying innovation subsidies and how their effect interacts with global warming. As we discussed above, because technology diffuses across locations, investments in innovation are not optimal and so innovation subsidies may raise welfare. Throughout we analyze innovation subsidies that reduce proportionally the innovation cost of firms. The subsidies are paid for using lump-sum taxes charged to all residents so, as with energy taxes, they do not introduce wealth effects. Of course, innovation subsidies distort innovation decisions and encourage firms to innovate more. Table 5 presents computations where we introduce innovation subsidies in both industries.

³³For comparison purposes, Golosov et al. (2013) find an optimal tax of around 50\$ per ton of coal using a discount rate of 0.985. Given the current coal price, this amounts to a tax of around 100%. Nordhaus and Boyer (2000) compute an optimal tax rate starting around 30% at the beginning of the 21st century, and rising to 180% by the end of the century. In contrast to these papers, our model emphasizes adaptation through mobility and predicts optimal taxes that are several times higher.

Figure 16. Contour Plots of Emp. Shares and Agr. Productivity with Energy Taxes ($\nu_1 = 0.0012$)

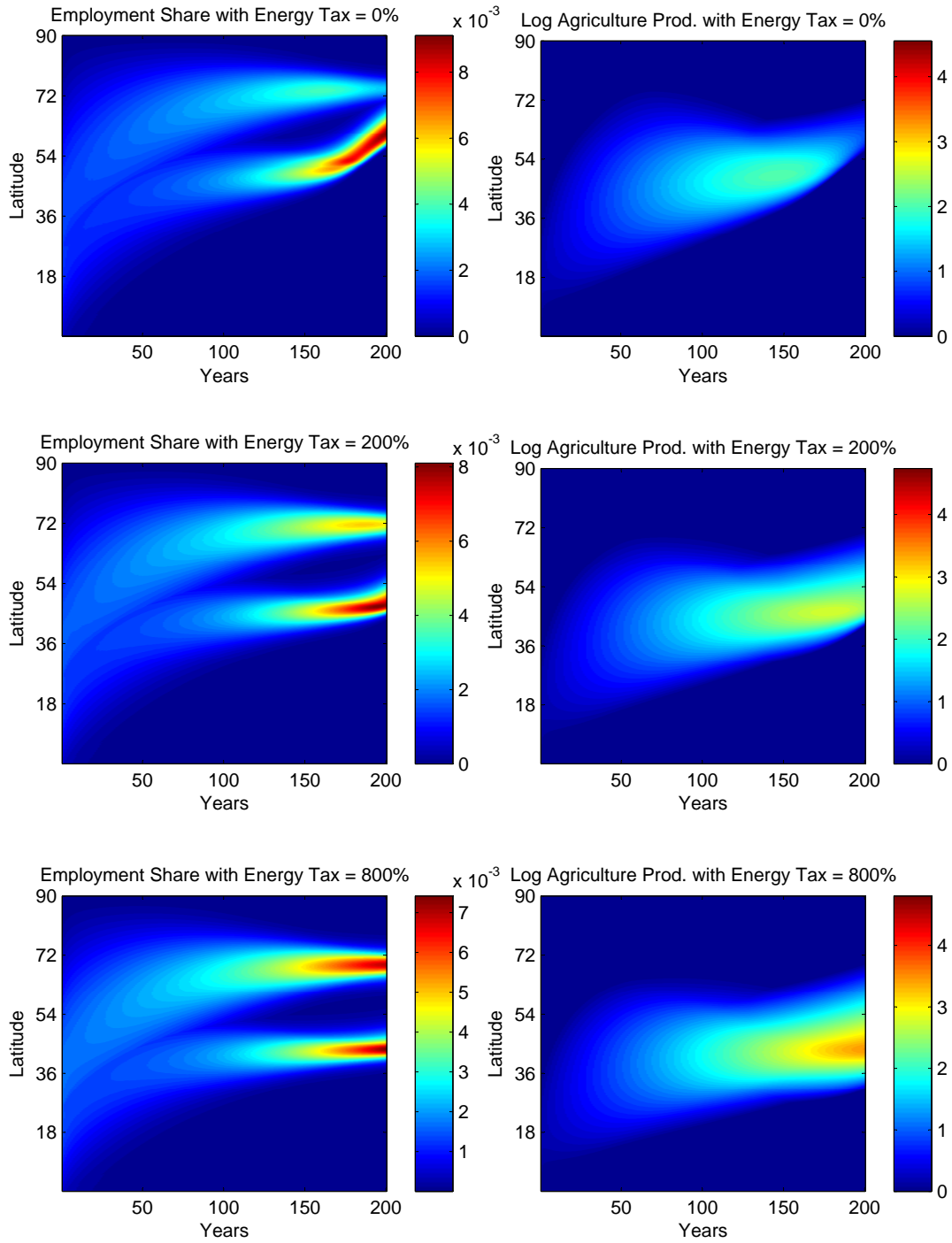
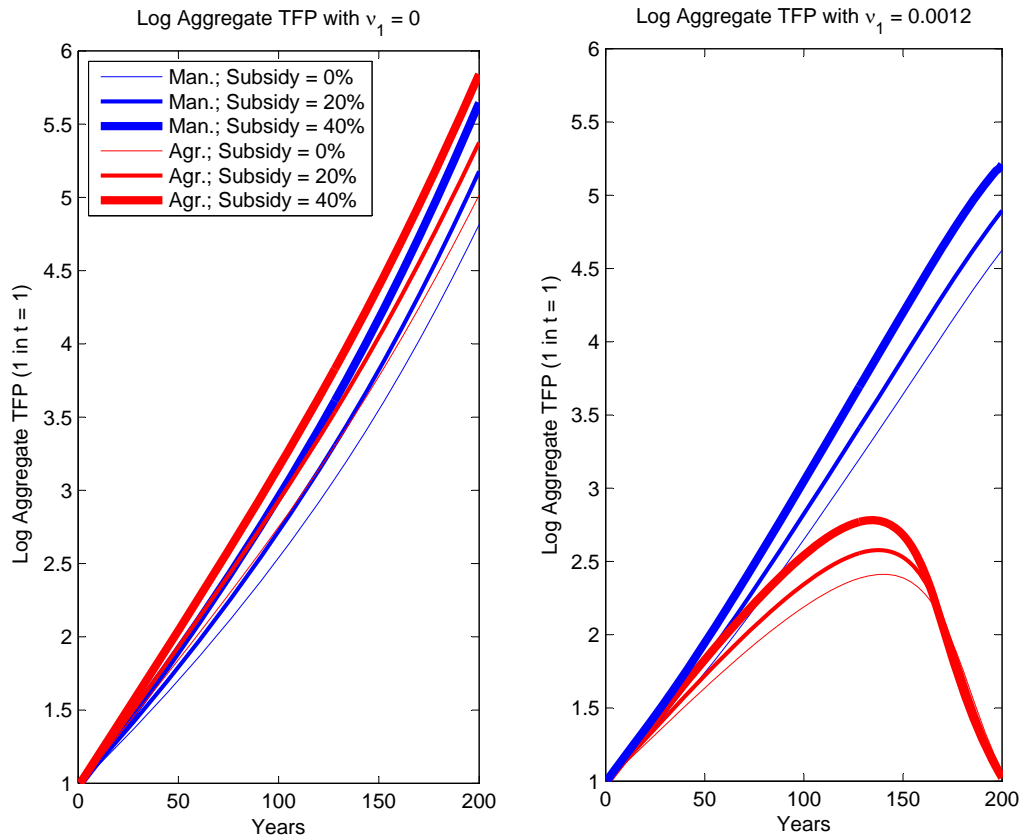


Table 5 shows that for subsidies of 20% and 40%, welfare increases for all the alternative values of ν_1 . That is, subsidizing innovation is always better than not subsidizing it. Furthermore, the larger the value of ν_1 , and so the larger the effect of pollution on temperature, the lower the effect of the subsidy on welfare when we subsidize both industries. So in contrast with the energy tax analyzed above, the increase in welfare associated with the policy is smaller, the larger the impact of pollution on temperature. The contrast is interesting since it underscores the importance of introducing space in the analysis of the economic effect of temperature increases. Innovation subsidies make firms innovate more, which leads to welfare gains, since in equilibrium they do not innovate enough due to the externality. However, they innovate more in regions that will become too hot in the future to be efficient for production. That is, as production shifts north, past innovation in the south is rendered useless. This effect reduces the impact of innovation subsidies and is larger the greater is ν_1 .

The economic phenomenon described above is evident when we look at aggregate growth in each sector. First, it is stronger in agriculture than in manufacturing, since global warming affects the agricultural sector more. The innovation subsidy always increases aggregate output growth in both sectors but does so less the higher the impact of carbon on temperature. For $\nu_1 = 0.0012$, the subsidy has no effect on average output growth in agriculture. In this case global warming completely eliminates 200 years of output growth in agriculture with or without the subsidy.

Figure 17. Aggregate World Productivity with Innovation Subsidies ($\nu_1 = 0$ and $\nu_1 = 0.0012$)



To explore this further, Figure 17 presents the time paths of aggregate productivity for the different sizes of the subsidies and $\nu_1 = 0$ and $\nu_1 = 0.0012$. For $\nu_1 = 0$ we see that the larger the subsidy, the larger the growth rate of productivity. In contrast, when $\nu_1 = 0.0012$, this is only the case in manufacturing but not in agriculture. In agriculture productivity first increases and then decreases due to global warming: the regress in productivity that we highlighted above. The innovation subsidy increases the rate of growth in agriculture initially, but this amplifies the impact of global warming, leading to productivity that ends up at the same level after 200 years, independently of the innovation subsidy. In this sense, innovation subsidies do not help ameliorate the catastrophic effects of global warming. Energy taxes are much more effective for this purpose.

7. CONCLUSION

This paper provides a framework to analyze the spatial impact of global warming in a dynamic context. We model a hemisphere of the Earth and calibrate the model using current data and a variety of projections on temperature and economic growth. Our model is one in which changes in specialization –induced, for example, by global warming– have long-lasting effects through their impact on innovation and the resulting local technological improvements. Even though global warming interacts with specialization patterns and innovation in complex ways, one of its main effects is to shift production and population to the north as it makes some of these regions warmer. Since technology is better in the north, in the absence of migration restrictions, temperature change can lead to small positive welfare effects. So if the impact of pollution on temperature is small, an economy can gain from temperature change. If, on the other hand, the effect of carbon emissions on temperature is very large, the welfare cost can be substantial. We find that these conclusions are affected in a significant way by the presence of migration restrictions and other frictions. Hence, our analysis suggests that part of the policy debate on global warming should focus on addressing some of these complementary frictions.

Our model features two externalities. The first one is related to technology diffusion and the second to energy use and carbon emissions. Due to these two externalities policy can be welfare enhancing (as can other frictions). We find that energy taxes should be large and are particularly useful to stop some of the consequences of global warming. Due to their interaction with specialization patterns and the corresponding innovation choices, such taxes can lead to positive (though small) growth effects and overall welfare gains. Energy taxes also result in large reductions in the stock of carbon, which could generate other health and consumption-based benefits that are not accounted for in our setup. In contrast, innovation subsidies also lead to welfare gains, but they have a more limited role in preventing some of the catastrophic effects of global warming in extreme scenarios. This is partly because we do not allow for energy-saving technological change or elasticities of substitution between inputs in production different than one. Extending the framework to add any of these two policies is a natural next step.

Rather than being exhaustive in including all relevant aspects of climate change, our goal has been to make progress in providing a framework that can jointly analyze some of what we believe are the most relevant margins of adjustment to global warming: migration, trade, and innovation. To

the extent that previous studies have not incorporated these important margins, their quantitative implications are necessarily subject to further refinements. The same applies to our work. Drawing on the IPCC and existing integrated assessment models, we focused on the rise in mean temperature and its effect on productivity as the most direct expressions of climate change. But we inevitably left out other important issues, such as rising sea levels, the likelihood of more extreme weather, and the possible violence related to large-scale migration. Given the spatial interactions between specialization, innovation, migration and global warming that we have uncovered, we hope others will help us take on the task of including many of these aspects in the future.

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APPENDIX: AN ALTERNATIVE CALIBRATION OF THE LINK BETWEEN EMISSIONS AND TEMPERATURE

Allen et al. (2009) and Matthews et al. (2009) have shown that the relation between temperature and cumulative emissions is essentially linear. That is, we can summarize all carbon cycle feedbacks and climate feedbacks with a simple linear relationship. This is not exactly consistent with the calibration we use in the main text since we choose $\nu_2 = 0.5$ and $\varepsilon_1 = 0.9975$. A value of $\varepsilon_1 \neq 1$ implies that temperature is a function of the carbon stock and not of cumulative emissions. Furthermore, it implies that the stock of carbon is computed as the sum of emissions minus the fraction that is eliminated over time. This is a simplification of the much more complex carbon cycle, and it takes the simple view that the carbon stock follows an AR(1) process. If we make $\varepsilon_1 = 1$, then the function $P(\cdot)$ just captures cumulative emissions which in turn determines temperatures. Given the definition of $P(\cdot)$, implied by our choice of ε_1 , a value of $\nu_2 < 1$ implies that temperature in period t is a concave function of $P(t)$. The model we have put forward includes the relationship advocated by Allen et al. (2009) and Matthews et al. (2009) as a special case when $\nu_2 = \varepsilon_1 = 1$.

In this appendix, we set $\nu_2 = \varepsilon_1 = 1$ and recalibrate ε_2 , ν_1 and ν_3 so that cumulative emissions are equal to 1600 GTC in 2100, as implied by the IPCC Special Report Emissions Scenarios (2000), and we obtain a 2° increase in temperature in the Equator and a 6° increase in the North Pole in 2100 in the baseline case (same as in the main text and consistent with IPCC, 2007). The result is $\varepsilon_2 = 0.000002475$, $\nu_1 = 0.000003$ and $\nu_3 = 1/42$ (as before). One caveat with this calibration is that cumulative emissions vary little with ν_1 .³⁴ The value we select yields cumulative emissions of 1603 GTC in 2100 while a value of $\nu_1 = 0.000006$ yields cumulative emissions equal to 1599 GTC by 2100. We selected the former as a baseline case since it yields temperature increases after 200 years more in line with the ones in the literature and with the model in the main text, although we present results below for several values of ν_1 . Note also that the values of ν_1 in this calibration are two orders of magnitude smaller. The reason is that the stock of carbon is smaller than cumulative emissions and $\nu_2 = 1$. These values yield identical temperature targets in year 2100 as those in the main text.

Table 6 presents the results of the Allen et al. (2009) and Matthews et al. (2009) ($\nu_2 = 1$ and $\varepsilon_1 = 1$) calibration, as well as the results for the calibration in the main text ($\nu_2 = 0.5$ and $\varepsilon_1 = 0.9975$) for comparison purposes. The results are very similar. Welfare peaks at the baseline case when $\beta = 0.98$, but it peaks at double the value of ν_1 when $\beta = 0.95$. Furthermore, the increases in temperature after 200 years when we multiply the baseline value of ν_1 by two, three or four, are also very similar.

One noticeable difference is that welfare is lower with the new calibration. The reason is simple: global warming is now a phenomenon that advances unabated. Humanity will eventually burn since temperature will grow unboundedly as long as the economy keeps using energy to produce. Given that we do not give producers any alternative, the faster increase of cumulative emissions than the stock of carbon yields smaller welfare. We view these two cases as extremes. The calibration in the text perhaps discounts the stock of carbon too much, while Allen et al. (2009) and Matthews et al.

³⁴As in the main text we report values of ν_1 after dividing by $1000/(\pi/2)$.

(2009) assumes a linear relationship between cumulative emissions and temperature independently of the levels of both of these measures. Other, more involved, representations of the carbon cycle, such as Golosov et al. (2013), will yield outcomes in between. However, given the small differences we compute between both of these formulations, the variation relative to the cases we present here will be small and is unlikely to change any of our conclusions.

Table 6. Alternative Calibrations of the Link Between Emissions and Temperature

Calibration		ν_1				
$\nu_2 = 0.5$ and $\varepsilon_1 = 0.9975$		0	0.0003	0.0006	0.0009	0.0012
	$T(0, 200) - T(0, 1)$	0	2.9215	5.7651	8.3875	10.2266
	$T(\frac{\pi}{2}, 200) - T(\frac{\pi}{2}, 1)$	0	8.7471	17.2608	25.1122	30.6187
	Welfare ($\beta = 0.95$)	0.7179	0.7247	0.7259	0.7176	0.6949
	Welfare ($\beta = 0.98$)	1.6096	1.6522	1.6449	1.5295	1.1906
$\nu_2 = 1$ and $\varepsilon_1 = 1$		0	0.000003	0.000006	0.000009	0.000012
	$T(0, 200) - T(0, 1)$	0	2.9701	5.8043	8.2673	9.7784
	$T(\frac{\pi}{2}, 200) - T(\frac{\pi}{2}, 1)$	0	8.8926	17.3781	24.7523	29.2766
	Welfare ($\beta = 0.95$)	0.7179	0.7205	0.7209	0.7188	0.7138
	Welfare ($\beta = 0.98$)	1.6096	1.6216	1.5685	1.4902	1.2298