Local Carbon Policy[*]

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Abstract

We study local carbon policy to address the consequences of climate change. Standard analysis suggests that the social cost of carbon determines optimal carbon policy. We start by using the spatial integrated assessment model in Cruz and Rossi-Hansberg (2024) to measure the local social monetary cost of CO_2 emissions: the Local Social Cost of Carbon (LSCC). Although the largest welfare costs from global warming are concentrated in the warmest parts of the developing world, adjusting for the local marginal utility of income implies that the LSCC peaks in warm and high-income regions like the southern parts of the U.S. and Europe, as well as Australia. We then proceed to study the effect of the actual carbon reduction pledges in the Paris Agreement and the progress they can make in implementing the expressed goal of keeping global temperature increases below 2°C. We find that although the distribution of pledges is roughly in line with the LSCC, their magnitude is largely insufficient to achieve its goals. The required carbon taxes necessary to keep temperatures below 2°C over the current century are an order of magnitude higher and involve large implicit inter-temporal transfers. Increasing the elasticity of substitution across energy sources is important to reduce the carbon taxes necessary to achieve warming goals.

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1 Introduction

The impact of temperature increases caused by CO_2 emissions is, and will be, heterogeneous across locations of the world. Regions in Central Africa or India will experience large losses in welfare over the next few centuries while regions in the northern parts of Canada, Europe, or Russia could benefit from rising temperatures. Hence, from a particular region's perspective, the social need for climate policy can vary substantially. What are the incentives to impose carbon taxes across locations of the world? How are these incentives related to actual pledges in the Paris Agreement? What are the implications of these pledges for aggregate temperatures and the economies of different regions across the globe? In this paper we explore these questions using the spatial integrated assessment model in Cruz and Rossi-Hansberg (2024).

The social cost of carbon has become the standard measure to benchmark the magnitude of the carbon taxes needed to implement optimal carbon policy. It measures the social cost in U.S. dollars of adding a ton of CO_2 to the atmosphere. If we were able to measure this social cost accurately, standard Pigouvian logic tells us that the optimal tax should be such that the price of carbon is equal to this social cost. Since carbon emissions are a global externality there is, at least in principle, a world's social cost of carbon that takes into account all the implications of the additional ton of CO_2 throughout the world and over time. The price of carbon should then be set at this price, everywhere. Of course, this logic is correct only from a global planner's point of view, where the planner puts equal weights across individuals. Its implementation requires transfers from the regions that are less affected, or positively affected, by CO_2 emissions to the countries that are negatively affected. In practice, countries and regions tend to consider the implications of climate change for themselves, not for the whole world. Their incentives to pursue climate policy via carbon taxes, reflect their own evaluation of the social cost of carbon, not necessarily the world's. To understand what these incentives are today, we start by computing the Local Social Cost of Carbon (LSCC) at a resolution of $1^\circ \times 1^\circ$ across the globe for the year 2022.

The LSCC is determined by the local willingness to pay for the effects caused by an additional ton of CO_2 emissions.[1] It can be decomposed in two parts: the welfare cost of the additional carbon emissions and the inverse of the marginal utility of income. The latter component allows us to express the LSCC in dollars per ton of CO_2, rather than utils per ton of CO_2. In Cruz and Rossi-Hansberg (2024), we have argued that the welfare costs of climate change are extremely heterogeneous across locations due to the different local temperature effects from increases in average world temperatures, from differential effects on amenities, productivity, and natality of changes in local temperatures, and from the differential cost of migration and trade across regions of the world. Measuring these welfare costs requires a framework encompassing the full range of impacts of CO_2 emissions, from the implied increases in local temperatures to their effects on regional economies, accounting for the costly mobility of agents, changes in trade patterns, and future local investments and growth. We employ the framework developed by Cruz and Rossi-Hansberg (2024)

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[1] Specifically, we quantify, in dollars per ton of CO_2, the current and future local per capita costs (or benefits) of perturbing the *business as usual* path of carbon dioxide emissions by one ton in the year 2022.

as it allows us to compute the LSCC at a fine level of resolution and accounts for a number of adaptation mechanisms over time.

The welfare implications from global warming are particularly large for developing countries close to the Equator, where temperatures are higher. Central Africa and parts of Central and South America, as well as South East Asia are particularly negatively affected. The LSCC combines this heterogeneity with the spatial heterogeneity in the inverse of the marginal utility of income. This value is naturally small in today's rich regions since people obtain more of their welfare from consumption rather than from amenities or migration.[2] The division of these two effects determines the LSCC.

The resulting geography of the LSCC is very different than the geography of the welfare losses from additional emissions due to the marginal utility of income component. This component increases the LSCC in productive countries relative to their overall welfare losses from warming, and has the opposite effect in developing countries which are less productive. Therefore, the LSCC is high in the warmest places of rich areas, like the south of Europe or the U.S. and Australia, and in middle income countries like Brazil, Mexico, and South Africa. In Northern Canada and Russia, the effect of welfare makes the LSCC negative in the baseline *business as usual* scenario. In more extreme scenarios, the LSCC is positive everywhere but its geography is similar.

Of course, any calculation of the social cost of carbon requires taking a stand on the relevant intertemporal discount factor. In fact, the global social cost of carbon, as well as the LSCC, are extremely sensitive to the value of this discount factor. As we move the discount factor from 0.965 to 0.97, the global social cost of carbon goes from about 5 to 50 dollars ($) per ton of CO_2.[3] The permanent growth rate in the baseline scenario is 2.97%, so we cannot increase it much further. Regions in the upper 1% of the distribution have much larger LSCC, ranging from about 30$ to 150$ as we vary the discount factor.

We then turn to studying local carbon policy and its effects. Our starting point is the geography of the LSCC which determines the local incentives to tax carbon if the location could unilaterally determine *global* policy without creating any additional distortion from the local tax rebate. Of course, each region setting carbon prices at the LSCC level is not necessarily the optimal policy since it only considers each region's own social cost and does not internalize the policy actions of others. Unfortunately, we cannot solve the planner's problem and determine optimal local carbon policy directly since the dynamics of the model are too complex. Furthermore, because the equilibrium spatial distribution of economic activity is not optimal due to static and dynamic externalities, the carbon taxes and the transfers resulting from the tax revenue rebates can affect the efficiency of the spatial distribution and therefore the cost of the tax. This makes the optimal policy potentially spatially heterogeneous and likely complex.[4] Instead, here we simply compare

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[2] In our model utility is linear in the consumption aggregate of varieties. However, the ability to move implies that utility equalizes across locations up to moving costs. Hence, amenities, which determine the marginal utility of income, are lower in productive places across location with small moving costs.

[3] Throughout the paper nominal values are expressed in year 2000 dollars.

[4] Note also that setting carbon prices at the LSCC level is not the unilateral optimal policy for a region. When setting carbon policy

the LSCC to the actual local pledges in the Paris Agreement for nine large regions for the period 2022 to 2030. The magnitude of these pledges is large in many of the areas where the LSCC cost is also large, so both policies have a similar, although by no means identical, spatial distribution. In particular, Europe and the U.S. made relatively large pledges. China did too, although its LSCC is small except in its more productive regions in the eastern coast.

In order to analyze the impact of the Paris Agreement, we first calculate the carbon tax equivalent of the carbon emission reduction pledge for a partition of the world in nine regions. We then study the effect of imposing these carbon taxes unilaterally. We find that CO_2 leakage can be positive or negative depending on the region. When regions that are large and rich, like the U.S. and Europe, impose unilateral carbon taxes their economies shrink. Their costs grow relative to other regions, which results in out-migration and lower levels of investments. The rest of the world slightly contracts and concentrates output in the most productive areas with high carbon prices. The result is a small decrease in real GDP in the rest of the world and a larger reduction in emissions. In contrast, when relatively low income per capita countries, like China, impose carbon taxes, leakage is positive and the rest of the world ends up emitting more CO_2.

We also analyze the case in which all regions implement their pledges in the form of carbon taxes simultaneously. The required carbon taxes are naturally larger in this case, since policy action leads to smaller reductions in local GDP due to the simultaneous actions of others. Overall, we find that these pledges reduce carbon emissions little relative to the baseline and that the effect on temperatures is small. Hence, they are not sufficient to keep temperature increases below 2°C relative to pre-industrial levels by 2050 and far from the level necessary to keep temperatures below 2°C by 2100. If all countries implement carbon taxes equivalent to their 2030 pledges permanently, temperatures by 2100 reach levels of more than 4°C relative to pre-industrial levels. Keeping the distribution of CO_2 emissions in the Paris Agreement constant, we estimate that the policy necessary to keep temperatures below 2°C by 2050 is, on average, more than two times larger than the policy required to reach the Paris Agreement. The policies needed to keep temperatures below 2°C by 2100 are an order of magnitude larger, and perhaps unrealistic. The average tax per ton of CO_2 would need to be as large as 500$. Such a policy implies a large inter-temporal transfer between current and future generations. World real GDP falls as much as 10% at impact, recovers and becomes larger than without the carbon policy only by 2150.

Carbon taxes are relatively ineffective at reducing carbon emissions because they tend to delay, rather than eliminate, carbon use. The reason is that carbon-based energy costs increase as the world uses more carbon. Larger taxes reduce use, and therefore delay this process. Cruz and Rossi-Hansberg (2024) explains this mechanism in detail. As carbon becomes more expensive due to carbon taxes, the world uses less carbon-based energy, but it does not eliminate its use completely since substitution is costly (particularly

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unilaterally, countries do not internalize the effect they have on the rest of the world. Unilaterally, regardless of their LSCC, small countries will want to set small carbon taxes since they know that their local emissions only have a negligible effect on global CO_2 emissions and global temperature. In contrast, unilateral policy will be closer to the LSCC for large countries that internalize more the effects that their policy will have on global emissions and temperature.

in certain industries and uses). We model this substitution using a constant elasticity of substitution in the energy production process with fossil fuels and clean energy as inputs. The elasticity of substitution in this function is crucial in determining the timing of carbon use and the effectiveness of the tax in delaying its use. We use a value of 1.6 in our baseline scenario but present results also for the case when it takes the value of 3. Of course, this elasticity is partly a policy variable. Policy can incentivize the use of equipment that can more easily substitute between both types of fuel, for example, electric cars and buses.

Our paper is the first one to discuss the LSCC at such a high spatial resolution, considering costly migration, costly trade, and local investments in a model with a fully fledged economic geography and a rich set of agglomeration and congestion forces. Tol (2011) surveys the literature on the economic impacts of climate change and the different methods employed to estimate the impact of climate change on human welfare. Nordhaus (2017) computes the social cost of carbon in the global economy. Carleton and Greenstone (2022) provides a set of guidelines to compute the global social cost of carbon. Carleton et al. (2022) estimate age-specific mortality-temperature relationships and compute a mortality *partial* social cost of carbon. Hassler et al. (2020) discusses carbon pricing in the Swedish context.

The rest of the paper is structured as follows. Section 2 outlines the key elements of the economic and climate model and its quantification. Section 3 quantifies the LSCC and describes how it varies across damage levels and discount factors. Section 4 discusses the efficiency of the Paris Agreement to limit warming and explores different combinations of environmental policies to reduce the temperature path. Section 5 concludes.

2 Model and Quantification

In order to analyze the local effects of environmental policies we need a spatial dynamic model of global warming with a realistic geography. Cruz and Rossi-Hansberg (2024) develops such a framework. It extends the model in Desmet et al. (2018) to incorporate endogenous population growth and energy as an input of production. It also incorporates a climate component through a carbon cycle, and the effect of the implied temperature changes on amenities, productivity, and natality rates. Instead of presenting the full model, here we limit ourselves to briefly describe the main elements of the model and its quantification. We refer the reader to the paper for a technical description.

Figure 1 describes the workings of the model. The components in black denote the baseline model from Desmet et al. (2018) and the components in green represent the additions by Cruz and Rossi-Hansberg (2024). We divide the land mass of the world in 17,048 locations, with a resolution of $1^\circ \times 1^\circ$. Each location is unique in terms of its amenities, productivity, geography, as measured by its bilateral transport costs to all other regions and the migration frictions to enter them, as well as its climate conditions. Agents derive utility from consuming a continuum of a fixed set of varieties and from common and idiosyncratic amenities in their location of residence. If agents move, they pay migration costs in the form of a permanent utility discount that is log-linear in an origin and a destination effect. Agents supply land and labor inelastically to firms and receive the corresponding payments. Every period they face a consumption decision and a migration decision. The natality rate (birth minus death rate) at a location is determined by a location's income and temperature in order to capture demographic transitions and the effect that temperature can have on mortality.

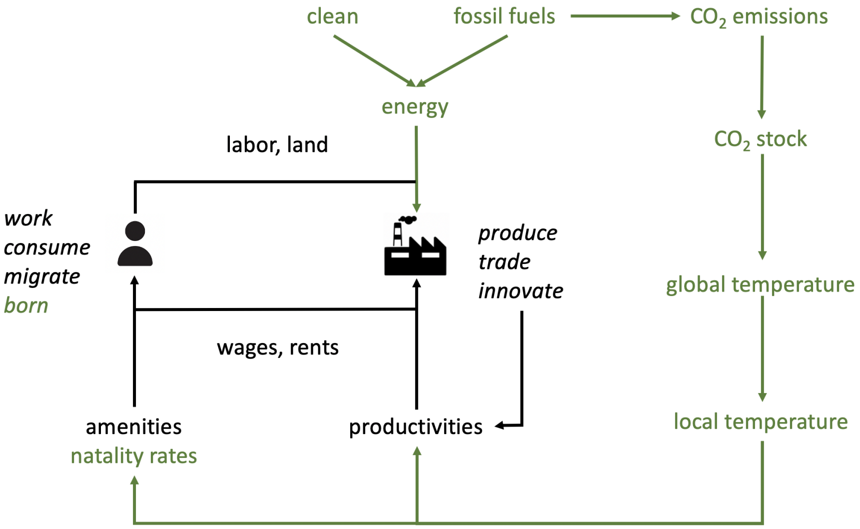

Figure 1: Model description

Firms in a location use land, labor, and energy as inputs to produce specific varieties that they trade with other locations subject to iceberg transport costs. They use a constant-returns-to-scale Cobb-Douglas technology in these three inputs. They generate the energy input by combining fossil fuels and clean energy sources using a constant elasticity of substitution technology with elasticity given by ϵ. Firm's productivity is idiosyncratic and drawn from a Fréchet distribution. The level of this distribution is determined dynamically by local production externalities, technology diffusion from other locations, and the firm's own innovation decisions. Firms can shift the distribution from which they draw their technology every period by paying an innovation cost. They compete to produce in a given location through competitive bidding. They innovate optimally to gain the bid, but end up with zero profits since they transfer all the surplus from innovation to the fixed factor, namely, land. Local residents are the owners of land and receive all land rents.

The result is a model in which congestion forces, which are determined by negative externalities of congestion in amenities, idiosyncratic preferences for location, and having land (a fixed factor) as an input in production, balance with agglomeration forces, given by local externalities, as well as dynamic agglomeration forces coming from the firm's investment decisions which are monotone in a firm's market size. Firm market size is determined by the distribution of expenditures discounted by the relevant transport costs. The presence of technology diffusion and externalities in productivity and amenities implies that the equilibrium allocation is not efficient, even without considering the climate externality. The equilibrium of the model is unique under some parameter restrictions that are satisfied in the quantification and amount to congestion forces ultimately dominating agglomeration forces.

The combustion of fossil fuels to generate the energy used by firms releases CO_2 emissions into the atmosphere, where they accumulate and warm up the Earth. We use the model of the carbon cycle in IPCC (2013) which determines the evolution of global temperature given firm's emissions. We set the prices of fossil fuels and clean energy in the year 2015 to target the observed CO_2 emissions and use of clean sources at the country-level. The local prices of clean energy and fossil fuels evolve with the world's technology frontier, with elasticities that replicate the evolution of their use in the world economy. The local price of fossil fuels also depends on extraction cost which are low when fossil fuels are abundant, but rise sharply as they become exhausted (as in Bauer et al., 2017). Local temperature variation is determined by aggregate temperature variation through a constant local down-scaling factor, as suggested by Mitchell (2003).

Changes in local temperatures affect amenities and productivity through damage functions estimated in Cruz and Rossi-Hansberg (2024). They determine the different semi-elasticities of changes in local temperature on amenities and productivity, conditional on the level of temperatures. They are estimated using a panel of model-implied local amenities and productivity over four years that control for all the adaptation mechanisms incorporated in the model. As such, they represent the effect of temperature on fundamentals, not on individual or firm reactions. The causal effect of temperature on amenities and productivity are estimated using a panel fixed effect empirical specification with regional trends. The estimated damage functions show that the semi-elasticity of temperature on amenities is about 2.5% in the coldest regions of the world, declines continuously and is negative and about the same absolute magnitude in the warmest places. Namely, in the warmest places on Earth a 1°C increase in local temperature decreases amenities by 2.5%. The damage function for productivity has a similar shape although the effects are larger and asymmetric with reductions of more than 10% in productivity in response to a 1°C increase in temperatures in the warmest regions. Finally, we specify local natality rates as a declining function of real income and as a bell-shaped function of temperature. Hence, when temperatures are extreme, natality rates are low and they are maximized in temperate climates.

The model quantification relies on data on the geographic distribution of population and income from G-Econ, the Human Development Index, and bilateral transport costs to construct measures of local productivity and local amenities that exactly rationalize this data through our framework. In addition, we estimate mobility frictions to match net local changes in population between 2000 and 2005. With the quantified model in hand, we can compute the cell-level welfare impact of increases in CO_2 emissions as well as the cell-level marginal utility of income, which allows us to measure the LSCC. We can also impose carbon taxes in any cell of the world and measure their impact.

3 The Local Social Cost of Carbon

The Social Cost of Carbon (SCC) is a central concept for understanding environmental policy, as it represents the global monetized value of all present and future net damages associated with a one ton increase in CO_2 emissions (Carleton and Greenstone, 2022). Therefore, its quantification depends on how comprehensive are the models to calculate it. We include the main channels through which CO_2 emissions can affect individuals, allow for several adaptation mechanisms, and do the proper aggregation from local to global effects. One limitation is that we only measure the part of the SCC associated with local temperature increases, but do not include the part associated with other related phenomena, like coastal flooding.[5] The cost of those effects should be added to the costs we compute here. Although we present implications of our model and a quantification of the SCC, we are more interested in the Local SCC (LSCC). The concept is similar, and it is still calculated in a global model, but it considers the monetized value of all local damages. Thus, it represents the extent to which global CO_2 emissions damage a particular location and, therefore, the level at which these regions should want to set a *global* carbon price.[6] Of course, in actual negotiations, countries will not necessary want to impose taxes that set the local price at this level, since they realize that there might be leakage to other regions if they do not impose a similar tax. Nevertheless, it does measure the local social incentives to price carbon.

We define the LSCC of region r at period t as

$$LSCC_t(r) = -\left. \frac{\partial W_t(r)}{\partial E_t^f} \middle/ \frac{\partial W_t(r)}{\partial w_t(r)} \right., \tag{1}$$

where

$$W_t(r) = \sum_{\ell=t}^{\infty} \beta^{t-\ell} u_\ell(r), \tag{2}$$

denotes local per capita welfare, $u_t(r)$ local per capita utility, $w_t(r)$ local per capita nominal income, E_t^f global emissions of CO_2, and β the discount factor (which we set to $\beta = 0.965$ in our baseline simulation since the balance growth path features real GDP growth of about 3%). The numerator represents the marginal local welfare impact of additional global carbon emissions and the denominator represents the marginal local welfare impact of an additional U.S. dollar adjusted by Purchasing Power Parity.[7] In sum, the LSCC equals the economic impact of a unit of emissions in terms of t-period nominal income.

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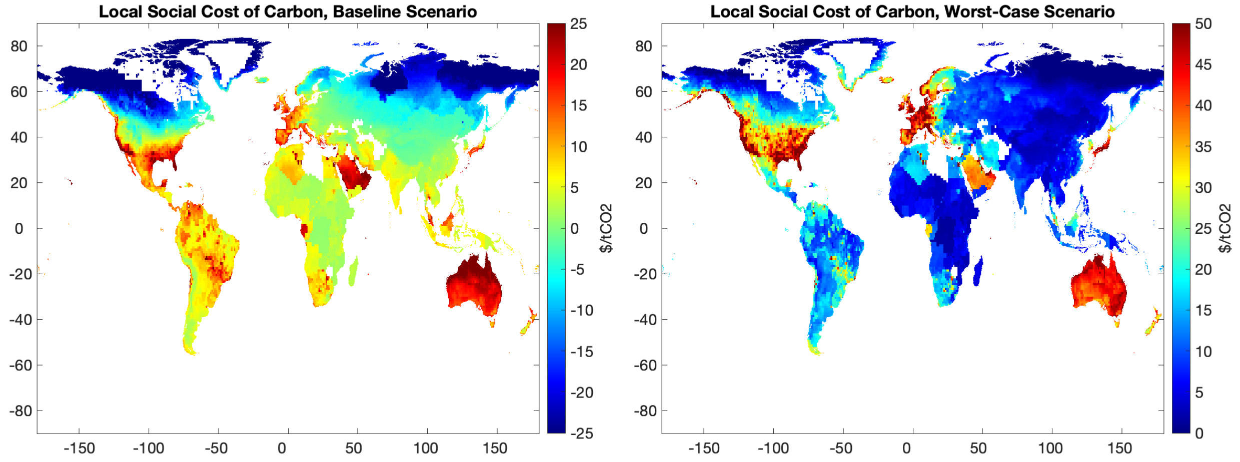
[5] See Desmet et al. (2021) for an evaluation of coastal flooding in a related framework.

[6] In other words, the LSCC represents the carbon tax a given region would impose in the whole world, if it were able to set environmental policy in each location of the world according to its own interests without creating any additional distortion through the local lump sum tax rebate.

[7] In our model, conditional on the level of amenities and migration costs, utility is linear in real income. We could easily extend the model to incorporate a period utility function that is concave in real income. This would increase the dispersion in the spatial and inter-temporal distribution of the marginal utility of income.

We compute the LSCC using a discrete approximation. Specifically, we consider our *business as usual* baseline path of emissions and increase the carbon dioxide emissions by one ton in the year 2022.[8] Then, we simulate the economy forward for four centuries and compute local welfare in 2022.We then repeat the exercise absent the pulse of carbon dioxide. The difference in welfare between these two scenarios approximates the numerator of equation (1). As for the denominator of equation (1), in order to express the LSCC in U.S. dollars adjusted by Purchasing Power Parities, we consider an increase in local income in 2022 assuming that it only affects current utility with no effects afterwards. More precisely, when local wage rises, we allow for the adjustment in prices and population, but take the fundamentals of the model (i.e., productivity, amenities, land endowment, energy prices, and trade and migration costs) as given.

Figure 2 displays the spatial distribution of the LSCC. We consider two different scenarios: the baseline scenario, defined by the point estimates of the damage functions on amenities and productivity described in the previous section, and the worst-case scenario characterized by the 95% lower confidence interval of the damage functions.[9] We present the LSCC in terms of dollars per metric ton of CO_2 ($\$/tCO_2$).[10]


Local Social Cost of Carbon, Baseline Scenario

Local Social Cost of Carbon, Worst-Case Scenario

Figure 2: Local Social Cost of Carbon in the baseline and worst-case scenario.

In the baseline scenario, the LSCC is positive in the warmest locations of the world and negative in the Arctic. The highest values of the LSCC are observed in the hottest and richest regions of the world: Australia, the Arabian Peninsula, and the south of Europe and the United States. All of them are high income locations that will experience intermediate welfare costs from temperature increases. Even though lower income locations in Sub Saharan Africa and India are expected to experience the largest welfare losses

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[8] We evaluate the LSCC in the year 2022, taking the level of population as fixed, because we are interested in understanding the current incentives to tax carbon. To assess future incentives to tax carbon, the LSCC could be computed for future periods, as well. We expect the LSCC to be higher, as most of the damages are predicted to occur in future periods (see Cruz and Rossi-Hansberg, 2024).

[9] In Appendix B, Figure 11 presents the distribution of the LSCC, Figure 12 displays the LSCC in the best-case scenario, characterized by the 95% higher confidence interval of the damage functions and Table 5 displays the LSCC by country for the baseline and worst-case scenario and for different discount factors.

[10] A ton of CO_2 contains 0.2727 tons of carbon (tC), so a LSCC of $10\$/tCO_2$ is equivalent to $36.67\$/tC$.

from global warming, the LSCC of these places lies between 2$ and 5$ only. The LSCC in the worst-case scenario exhibits a similar pattern with a larger spatial dispersion and higher average values. The SCC, or the population weighted global average of the LSCC, takes the values of 5.28$/tCO$_2$ and 14.81$/tCO$_2$, respectively, where the global average uses as weights the population shares in the year 2022.[11] Of course, these averages depend heavily on the chosen discount factor, an issue that has been extensively discussed in the literature (see Carleton and Greenstone, 2022 for a summary) and to which we return below.

The structure of the damage functions suggests that the largest welfare losses in amenities and productivity occur in the hottest locations of the world. This logic might suggest that the LSCC should also be higher in the tropical areas and gradually decline in colder locations. However, the spatial distribution of the LSCC shows the largest values in high income locations that experience negative but not the most extreme welfare losses. To disentangle the forces shaping the LSCC, we decompose this term into the percentage change in welfare derived from the pulse of CO$_2$ (the welfare component), the monetization from utils to dollars (the inverse marginal utility or monetization component), and the unit adjustment; namely,

$$\begin{aligned} LSCC_t(r) &= -\left(\frac{\Delta W_t(r)[\Delta E_t^f]}{1\ \text{tCO}_2}\right) \Big/ \left(\frac{\Delta u_t(r)[\Delta w_t(r)]}{1\ \$}\right) \\ &= -\left(\frac{\Delta W_t(r)[\Delta E_t^f]}{u_t(r)}\right)\left(\frac{\Delta u_t(r)[\Delta w_t(r)]}{u_t(r)}\right)^{-1}\left(\frac{1\ \$}{1\ \text{tCO}_2}\right), \end{aligned}$$

where $\Delta W_t(r)[\Delta E_t^f]$ denotes the change in $W_t(r)$ as a result of the change in carbon emissions, E_t^f, and $\Delta u_t(r)[\Delta w_t(r)]$ the change in utility as a result of the change in income, $w_t(r)$.[12] The left panel of Figure 3 illustrates the percentage change in welfare derived from the pulse of CO$_2$. The figure resembles the spatial distribution of welfare losses from global warming (see Figure 8 in Cruz and Rossi-Hansberg, 2024), as temperature increases have the most pernicious effects in the warmest and poorest locations and the most favorable effects in northern locations. The highest income regions are at a cusp where the effects are relatively small, but negative. The right panel of Figure 3 illustrates the monetization, or inverse marginal utility component, which is related to local wages, local migration costs, and amenities. The main effect is that a higher level of income is associated with lower marginal utility. That is, a larger increase in income is required to achieve a given increase in utility. Note that this component is also large in magnitude relative to the welfare component, and always positive. The balance of these two components implies that the LSCC is the highest in hot, but also relative rich regions. A good example of this balance is the South of U.S., where the welfare effects are marked yet not extreme, but where the low marginal utility of income

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[11] The SCC is defined as the current and future costs of a pulse of CO$_2$ by an average household in the world. Accordingly, we compute it as the global average of LSCC weighting each location by its population share. The total global damage per unit of carbon can be defined as the SCC times the level of worldwide population. In this sense, total local damages scale the LSCC according to the level of local population. When considering two locations with similar LSCC, the more densely populated location would experience larger total damages.

[12] Appendix A formally derives the monetization component in terms of the wage and utility level.

yields one of the largest LSCCs in the world.

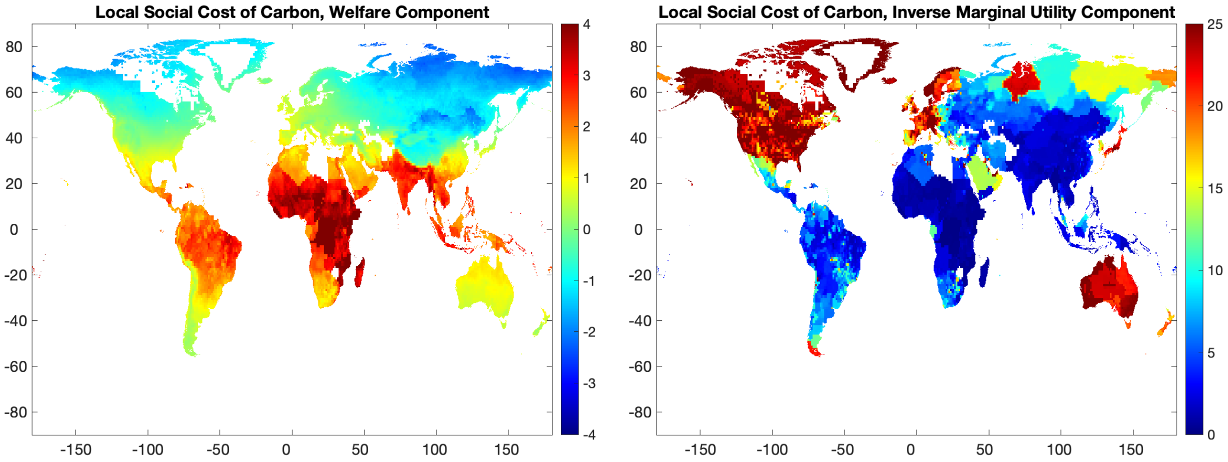

Figure 3: Decomposition of the Local Social Cost of Carbon in the baseline scenario.

Global warming is a protracted phenomenon with long lasting consequences. Hence, the discount factor we use plays a crucial role in determining the magnitude of the LSCC, although it plays less of a role in its spatial distribution described in Figures 2 and 3. In our framework, the discount factor has a role in the aggregation of inter-temporal effects from carbon emissions, but it has no allocative effect since all decisions ultimately are reversible or are independent of future outcomes. Hence, decisions on the level of the discount factor are purely decisions on the relevant social welfare function for inter-temporal aggregation; the choice answers the question, how do we value the welfare of future generations of humans today? Because our model features permanent growth and the utility function is linear in consumption, β is bounded by the inverse of the growth rate of real GDP. In the baseline scenario, the growth rate in the balanced growth path (BGP) of the economy is 2.97%[13] and thus the discount factor cannot exceed 0.97. Future generations will be richer, so we cannot value them too highly and still have well defined present discounted values.

Figure 4 presents the LSCC in the baseline and worst-case scenarios for different values of the discount factor. The solid line denotes the global population weighted average, which provides a measure of the global SCC. A global carbon tax should target this level if the welfare criterion is a utilitarian world planner.[14] The shaded areas represent the spatial heterogeneity across regions of the world. Clearly, higher discount factors rise both the average and the standard deviation of the LSCC. In the baseline scenario, with a discount factor of $\beta = 0.97$, the SCC is 50$ per ton of CO_2 emissions. However, this tax is too low for regions that include about 40% of the population of the world. The highest 1% of population would like a

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[13] The BGP growth rates are 2.98% and 2.96% in the worst-case and best-case scenarios, respectively.

[14] This is a local argument. As the economy evolves, the global SCC changes, and the optimal global carbon tax would change as well. Note also that the optimal policy would consider an optimal distribution of tax revenue rebates across space. We rebate the tax locally, which is not necessarily globally optimal. As discussed in the introduction, we have not develop a methodology to compute the optimal policy in this framework yet.

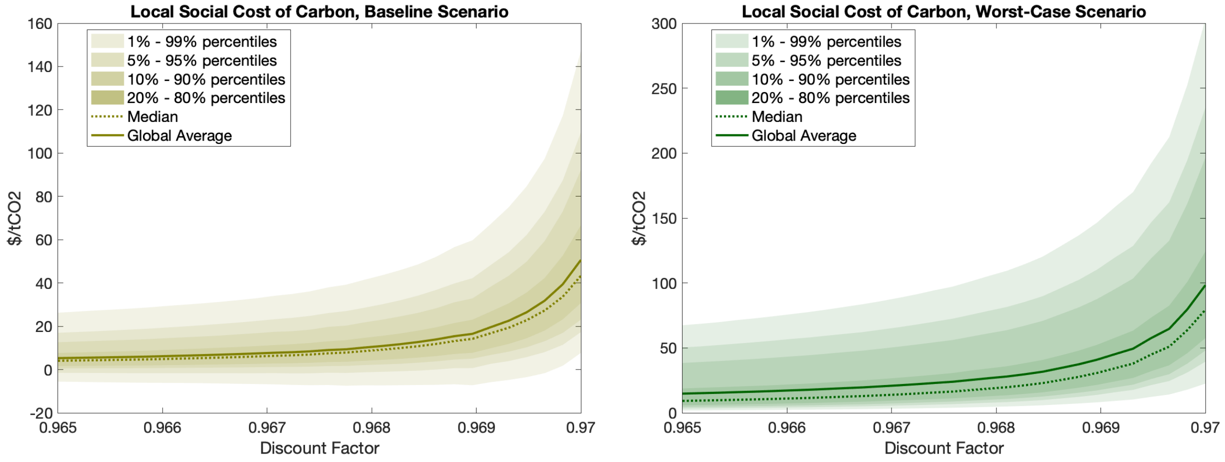

Figure 4: Local Social Cost of Carbon across percentiles in the baseline and worst-case scenario.

carbon price of about 147\$/tCO$_2$. Similarly, many locations, in fact 60% of the population since the distribution has a long right tail, would find the 50\$/tCO$_2$ carbon price too high according to their LSCC. The second panel of Figure 4 presents the same graph for the worst-case scenario. Now, the SCC for $\beta = 0.97$ is around 100\$/tCO$_2$, but the LSCC in the regions with the highest values is as large as 300\$/tCO$_2$. As in the baseline scenario, the skewness in the distribution implies that the average SCC would be too high for the majority (70%) of people (but also way too low for many others). Clearly, the distribution of the LSCC is relevant for studies of the political economy of carbon policy.

In light of our findings, we now turn to the analysis of actual carbon policy as reflected in the pledges embedded in the 2015 Paris Agreement and its stated goal of keeping global temperature increase below 2°C relative to pre-industrial levels.

4 Measuring the Impact of the Paris Agreement

In 2015, world leaders at the UN Climate Change Conference (COP21) signed the Paris Agreement, which has as objective to hold the increase in global average temperature well below 2°C relative to pre-industrial levels and pursue efforts to limit the temperature increase to 1.5° (UN, 2015). This goal is linked to a requirement that all countries design plans for climate action, known as nationally determined contributions (NDCs).[15] When countries submit their NDCs, they express their climate goals in an array of different measures. Therefore, it is challenging to compare what pledges really mean in terms of emission and, ultimately, temperature goals. In order to harmonize and model the diversity of climate goals, we follow King and van den Bergh (2019). They group NDCs into four categories: 1) Greenhouse gas (GHG) reductions relative to the emissions of a given year; 2) GHG reductions relative to a projected business as usual sce-

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[15] When preparing NDCs, some countries attached conditions (e.g., financial support or action in other countries) to the implementation of some measures. In the subsequent analysis, we restrict attention to the unconditional NDCs.

nario; 3) reductions in the intensity of GHG emissions per GDP; and 4) the implementation of projects to reduce GHG emissions. They normalize the emission pledges by expressing them as the implied emission reduction relative to emissions in the year 2015.

To simplify the interpretation of our results, in our implementation we aggregate the country-level pledges into 9 region-level pledges.[16] We also limit the scope of the pledges from all greenhouse gases to only CO_2 emissions from fuel combustion. We do so by multiplying the fossil fuel induced CO_2 emissions in the year 2015 by the ratio of the pledges for all GHGs in terms of the GHGs in the year 2015.[17] Figure 5 compares the observed CO_2 emissions in 2015 (yellow green bar), the projected emissions for the year 2030 in our baseline *business as usual* scenario (dark green bar), and the Paris Agreement emissions targets by 2030 (dark cyan bar).

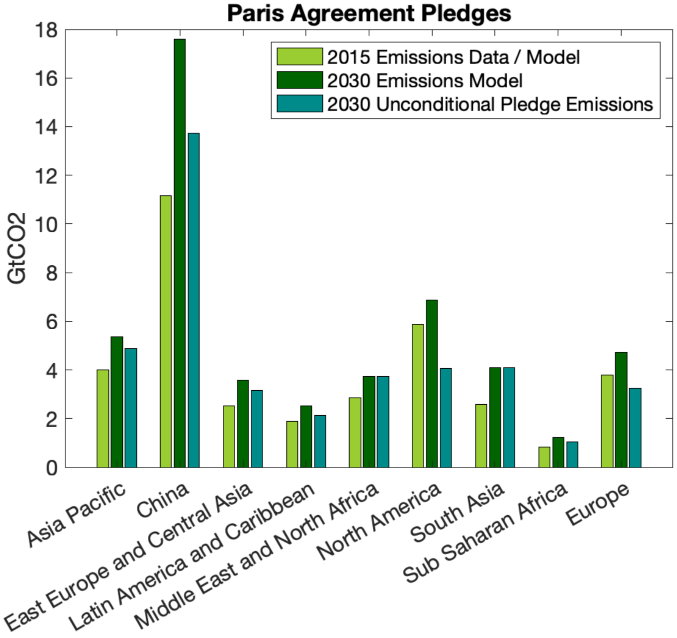

Figure 5: Paris Agreement Pledges.

Figure 5 shows that the pledges of China, North America and Europe are the most aggressive, followed by Asia Pacific, Eastern Europe and Central Asia, and Latin America. The pledges in the Middle East and Africa are either very small, or do not involve concessions according to our projections. We will implement these pledges in our model by finding the set of carbon taxes that implements these goals either unilaterally or collectively when all countries implement the Paris Agreement simultaneously. The second scenario is probably the most realistic, but the first one helps us discuss carbon leakage and its consequences.

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[16] Figure 13 in Appendix B illustrates the geographical composition of the regions.

[17] We perform this adjustment because our model only models the emissions of carbon dioxide from fuel combustion.

Unilateral Policy We start by consider the unilateral implementation of regional carbon taxes that achieve the Paris Agreement pledges. For each region of analysis, we find the carbon tax consistent with achieving the local pledge by 2030 (which requires solving a fixed point numerically). Here, we assume that the rest of the world introduces no environmental policy. The carbon tax is implemented in 2022 and increases over time proportionally to the evolution of fossil fuel prices.[18] Throughout, we assume that tax revenue is rebated locally as a lump sum transfer.

Region	**Carbon Tax** *($/tCO$_2$)*	**Δ%CO$_2$**		**Δ%Real GDP**	
		Own	**RoW**	**Own**	**RoW**
Asia Pacific	6.66	-9.08	-0.10	-1.32	-0.04
China	12.26	-21.94	0.63	-3.08	0.20
Eastern Europe and Central Asia	5.06	-12.55	-0.02	-1.84	-0.07
Latin America and Caribbean	17.53	-16.72	-0.11	-2.32	-0.03
Middle East and North Africa	0	0	0	0	0
Northern America	10.43	-40.5	-0.65	-5.87	-0.02
South Asia	0	0	0	0	0
Sub Saharan Africa	60.63	-14.93	0.12	-2.13	0.01
Europe	16.29	-30.60	-0.78	-4.24	0

Table 1: Unilateral carbon taxes to achieve the Paris Agreement pledges and their consequences.

The second column of Table 1 presents the carbon taxes, expressed in U.S. dollars per ton of CO$_2$, required to unilaterally comply with the Paris Agreement.[19] The third and fourth columns present the percentage decline in CO$_2$ emissions in the region itself (the Paris Agreement pledge) and in the rest of the world. The adoption of a carbon tax in a given region might induce more (highlighted in blue) or less (highlighted in red) emissions in the rest of the world. That is, carbon taxes might yield positive or negative carbon leakage! In contrast, as is clear from the last two columns, the effect on real GDP in the country that imposes the policy is always negative, and it might be positive or negative for other countries.

The conventional argument for carbon leakage indicates that higher carbon taxes abroad make domestic fossil fuels relatively cheaper, leading to an increase in CO$_2$ emissions and positive leakage. This effect dominates when China and Sub Saharan Africa impose a unilateral tax. However, the substitution effect of a carbon tax does not comprise the total effect. In addition, a higher carbon tax shifts production to regions that have different productivity and relative cost of carbon fuels. If the shift implies that production in the rest of the world is now concentrated in more productive regions (that use less inputs per unit of output) or regions with higher relative carbon prices, the result can be a reduction in emission. This second effect dominates for rich countries, like the U.S. or Europe. In these countries, the carbon tax shifts production to other regions of the world that are also very productive but that have relatively large fossil fuel costs.

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[18] The price of fossil fuels in each location is determined as the value that rationalize the local relative consumption of fossil fuels and clean energy. Thus, local prices represent an aggregation of the prices across different industries and energy sources. For a model with energy prices at the industry level, see Cruz (2023).

[19] Table 6 in Appendix B replicates Table 1 for an elasticity of substitution in the production of energy of $\epsilon = 3$.

Multilateral Policy: Implementing the Paris Agreement We now proceed to study the coordinated implementation of the Paris Agreement. In practice, we compute the set of carbon taxes that simultaneously meet the pledges in each region of the world. This requires solving numerically for a fixed point in the model implied carbon emissions for our 9 regions simultaneously. According to Table 2, a global average carbon tax of 12.47$/tCO$_2$ is required to achieve the pledges in the Paris Agreement. The largest carbon taxes are observed in North America and Europe, as these regions promised the largest declines in CO$_2$ emissions by 2030. The U.S. would need to implement a carbon tax of 49$ per ton of CO$_2$. Europe would need to implement additional carbon taxes of 32$ per ton of CO$_2$. Note that these taxes are required on top of the policy already in place in the *business as usual* scenario. China would need to introduce a smaller tax of 20$ per ton of CO$_2$. For all countries, except Sub Saharan Africa, the carbon tax required to achieve the Paris Agreement pledges in the simultaneous case is substantially larger than in the unilateral case, since real GDP in locations that implement carbon taxes declines less when other countries impose carbon taxes as well.

The results above depend crucially on the elasticity of substitution between clean energy sources and fossil fuels in the production function of the energy input, ϵ. Although in Cruz and Rossi-Hansberg (2024) we treat this elasticity as fixed, it is natural to think that its value can change with policy or with the characteristics of the capital stock. For example, if the car and bus fleet is electric, the energy it uses is perfectly elastic in fossil or clean energy sources. In contrast, gasoline base transportation requires fossil fuels and therefore is perfectly inelastic. The value we use in our baseline study, $\epsilon = 1.6$, is based on current evidence given installed technology,[20] but it is easy to envision that innovations or future investments can increase this elasticity substantially. Hence, in Table 2, we present the required taxes to implement the pledges in the Paris Agreement when $\epsilon = 3$. With a higher elasticity, firms can more easily shift energy use towards clean sources when faced with a carbon tax. Consequently, the same carbon pledges can be reached with a lower set of carbon taxes. On average, almost doubling the elasticity of substitution across energy sources reduces the carbon tax required to meet the Paris Agreement pledges by more than 20%. The largest proportional declines are experienced in the U.S. and Europe.

Figure 6 displays the evolution of carbon emissions and global temperature in the *business as usual* scenario and under the coordinated Paris Agreement implementation. It also presents, the evolution in the most extreme IPCC scenario, RCP 8.5. The figure shows that, even when the whole world commits to the Paris Agreement pledges, they only have a minuscule effect in reducing carbon emissions and limiting warming. Under the *business as usual* scenario, a global temperature increase of 2°C relative to pre-industrial levels is reached in the year 2043. The Paris Agreement delays the date at which we cross this threshold by only three years! That is, although the agreement might be politically consequential to build toward future agreements, the involved pledges are very far from achieving its stated goal.

As Figure 7 shows, the overall welfare effects of the Paris Agreement are correspondingly small. At im-

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[20] Papageorgiou et al. (2017) find that the elasticity of substitution for electricity generating industries is 2.

Region	**Carbon Tax** *($/$tCO_2$)* $\epsilon = 1.6$	**Carbon Tax** *($/$tCO_2$)* $\epsilon = 3$
Asia Pacific	6.89	6.93
China	20.25	19.72
East Europe and Central Asia	9.88	8.00
Latin America and Caribbean	13.91	4.31
Middle East and North Africa	0	0
North America	48.84	32.96
South Asia	0	0
Sub Saharan Africa	12.67	11.28
Europe	31.50	17.24
Global Average	**12.47**	**9.77**

Table 2: Multilateral carbon taxes to achieve the Paris Agreement pledges.

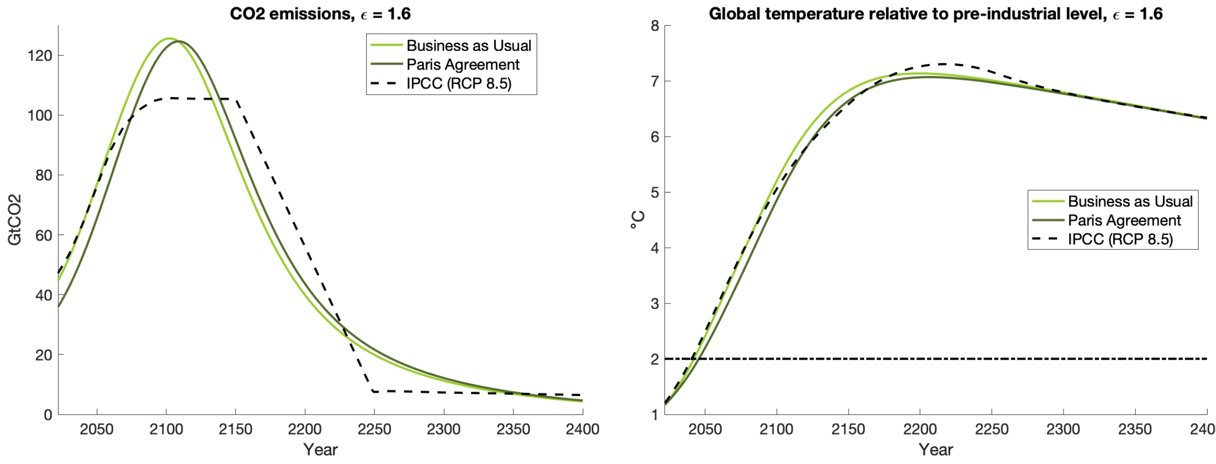

Figure 6: CO_2 emissions and Temperature under the Paris Agreement.

pact, the implementation of a carbon tax distorts the economy by making energy more expensive and thus reducing income and welfare. As time evolves, the flattening of the temperature curve has beneficial effects on amenities and productivity, leading to higher income and welfare. Implementing the Paris Agreement in 2022 has essentially no aggregate welfare effects, as the small future benefits of a lower temperature path are offset by the initial distortion originated by the carbon taxes. However, there is a re-composition of welfare across regions: the hottest and poorest regions –namely, North Africa and Middle East, Asia Pacific, Sub Saharan Africa, and Latin America– not only benefit from the lower temperature levels, but also from imposing relatively smaller carbon taxes. The Paris Agreement is, therefore, successful in reflecting equity in its implementation, as stated in its Article 2. It benefits the regions that will be hurt the most by global warming, although only marginally.

Staying Below the 2°C Target The results presented above make clear that the Paris Agreement is largely insufficient to limit global warming below 2°C. We now explore how large should carbon taxes be in order to attain this goal by a particular date. To this end, we find the set of carbon taxes that restrict global

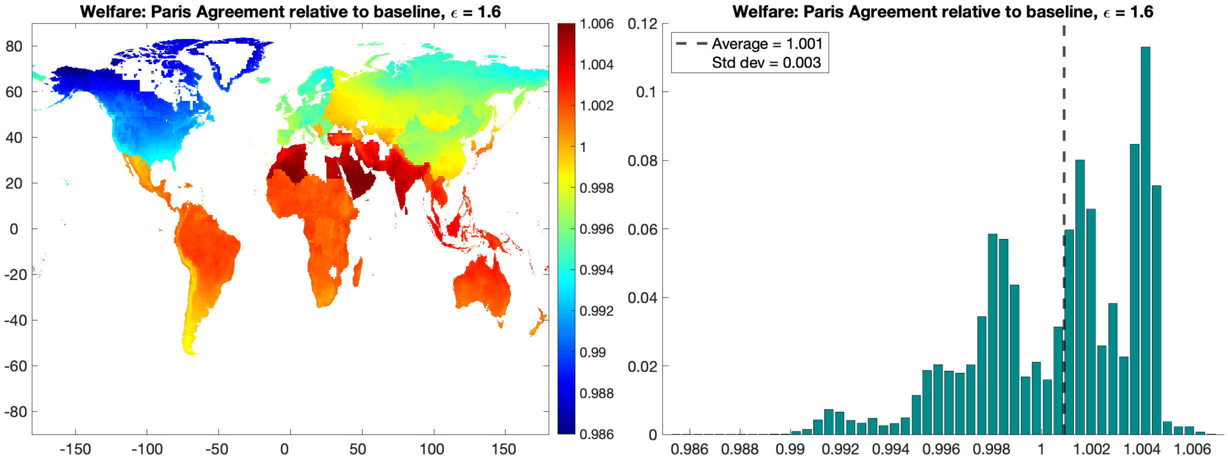

Figure 7: Welfare gains under the Paris Agreement.

temperature below 2°C by the year 2050 or 2100, considering the same distribution of CO_2 emission as those in the Paris Agreement.

Table 3 presents the carbon taxes required to reach these goals. To constrain warming below 2°C by 2050, the world requires an average carbon tax of 35.49\$/tCO_2. The carbon tax needed in North America becomes roughly 79\$ per ton of CO_2. The overall increase in carbon taxes delays crossing the 2°C threshold by 4 additional years (2050 rather than 2046). Doing so for another 50 years calls for carbon taxes that are on average 15 times larger. This magnitude seems extraordinarily high and indicates that reaching this goal by 2100 only using carbon taxes is unrealistic. Increasing the elasticity of substitution makes reaching the goal simpler, although still extremely hard. With $\epsilon = 3$ the average required carbon tax is roughly 246\$ per ton of CO_2, which is still enormous. Our conclusion is that achieving the stated goals of the Paris Agreement purely with carbon taxes requires levels of taxes that will be hard, if not impossible, to implement in practice. Plausible goals need to either be less ambitious, or require a policy mix that leads to much higher elasticities of substitution between fossil fuels and green energy sources.

Region	**Carbon Tax** (\$/tCO_2)			
	$\epsilon = 1.6$		$\epsilon = 3$	
	2050	2100	2050	2100
Asia Pacific	29.49	473.46	25.01	265.57
China	41.18	554.88	42.03	251.33
East Europe and Central Asia	31.18	483.31	25.22	219.36
Latin America and Caribbean	35.09	527.08	19.94	139.29
Middle East and North Africa	33.43	440.78	14.75	300.00
North America	78.59	653.59	50.57	205.72
South Asia	20.31	431.14	18.73	254.99
Sub Saharan Africa	36.96	513.19	28.29	309.98
Europe	59.51	634.98	35.40	199.45
Global Average	**35.49**	**506.54**	**28.36**	**246.43**

Table 3: Carbon taxes to reach warming of 2°C with the same distribution of CO_2 emissions of the Paris Agreement.

Figure 8 illustrates in solid lines the evolution of CO_2 emissions and global temperature across different scenarios under the baseline energy elasticity, $\epsilon = 1.6$. The figure shows that the main effect of a carbon tax is to reduce the use of fossil fuels at impact and to delay their use over time. Carbon taxes are able to achieve climate goals in the short- or medium-run, but unable to do so in the long-run. By the year 2300, the difference in temperature between the *business as usual* scenario and the scenario with the largest carbon taxes are minuscule. As explained in the introduction, and in more detail in Cruz and Rossi-Hansberg (2024), our constant elasticity of substitution specification implies that fossil fuels remain useful throughout. Furthermore, since the cost of extraction rises as more carbon is used, reductions in the use of fossil fuels delay the inevitable increase in extraction costs thereby incentivizing, not hindering, their use in the medium term. This implies that carbon taxes delay, but do not eliminate, carbon emissions in the long-run. Of course, this does not imply that carbon taxes are irrelevant. As Figure 8 illustrates, the aggressive carbon taxes required to keep temperature increases below 2°C by 2100 can reduce temperatures by 3 or 4 degrees Celsius for several centuries.

A higher elasticity of substitution is effective at delaying carbon use too, particularly in the long-run, as illustrated by the dotted lines in Figure 8. Since the price of clean energy falls at a faster rate than that of fossil fuels, a higher elasticity of substitution enables firms to consume more of the relatively cheap source of energy and less of the expensive one, leading to a flatter evolution of CO_2 emissions. As a consequence, the path of temperature increases slows down. In other words, the implementation of carbon taxes under a higher elasticity of substitution limits warming both in the short- and long-run (although ultimately all carbon gets used in this scenario as well). Hence, carbon taxes are much more effective if they are complemented with investments on technologies that rise the elasticity of substitution (i.e. technologies that reduce the storage cost of clean sources).

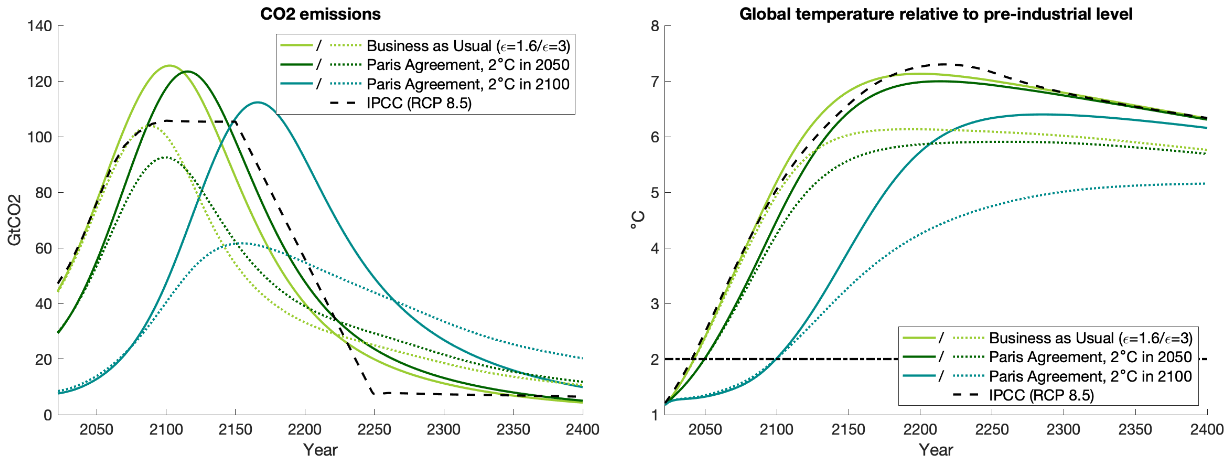

Figure 8: CO_2 emissions and Temperature under different warming targets and energy elasticities.

Table 4 presents the average and regional welfare consequences of the aforementioned environmental policies relative to the baseline scenario. Values below one indicate losses from imposing the corresponding

Region	Welfare			
	$\epsilon = 1.6$		$\epsilon = 3$	
	2050	2100	2050	2100
Asia Pacific	1.0019	1.0045	1.0030	1.0171
China	0.9973	0.9880	0.9982	0.9982
East Europe and Central Asia	0.9958	0.9750	0.9965	0.9858
Latin America and Caribbean	1.0009	1.0022	1.0037	1.0212
Middle East and North Africa	0.9996	0.9962	1.0028	1.0043
North America	0.9892	0.9715	0.9953	0.9943
South Asia	1.0048	1.0125	1.0049	1.0223
Sub Saharan Africa	1.0030	1.0159	1.0053	1.0288
Europe	0.9930	0.9779	0.9978	0.9984
Global Average	**1.0002**	**0.9996**	**1.0019**	**1.0121**

Table 4: Welfare gains from imposing the carbon taxes necessary to stay below the 2°C target with the Paris Agreement regional distribution.

carbon tax, while values above one indicate gains. As the global average indicates, in the aggregate using carbon taxes to stay below the 2°C target by 2050 has no welfare impact. North America, Europe, and some other regions lose a little, but other regions, primarily in Asia, gain slightly. Imposing policy to reach the 2°C target in 2100 leads to small losses. The losses in the U.S. and Europe are the largest, reaching values between 2% and 3%. The higher elasticity of substitution makes the policy uniformly better and leads to positive average welfare gains for the world. China, Europe, and the U.S. still lose, but the losses are small.

The small welfare effects from the pretty extreme policies required to achieve the 2°C Paris Agreement goals by 2100 in Table 4 also hide a substantial inter-temporal transfer across generations. In Figure 9 we present the time series of welfare and real GDP in the different Paris Agreement scenarios relative to our baseline. We focus on the original agreement which, as we have argued, has small effects and on the 2100 2°C target. As the figure indicates, in all circumstances the policy involves losses in the short-run due to the increased cost of production, and the corresponding discretionary effects, but gains in the future. In terms of welfare, for example, the 2100 target with our baseline elasticity of substitution implies declines in the short-run of as much as 8%. The welfare effect of the policy becomes positive by 2100 when the temperature consequences of the policy become more relevant. The effect on real GDP is more sobering: losses of about 10% in the short-run, and net positive gains by 2150. Carbon policy that can actually achieve the stated temperature goals in the Paris Agreement will require large inter-temporal transfers across generations.

5 Conclusions

Carbon taxes are widely proclaimed as the best solution to address climate change. The reason is simple, climate change is a global externality and, to solve it, we need to align the social and the private cost of carbon. This can be achieved by setting the global cost of fossil fuels at the level consistent with the global social cost of carbon. This logic is, of course, sound. Nevertheless, it disregards three important parts of the problem. First, the social cost of carbon emissions vary dramatically across space. The local social cost of

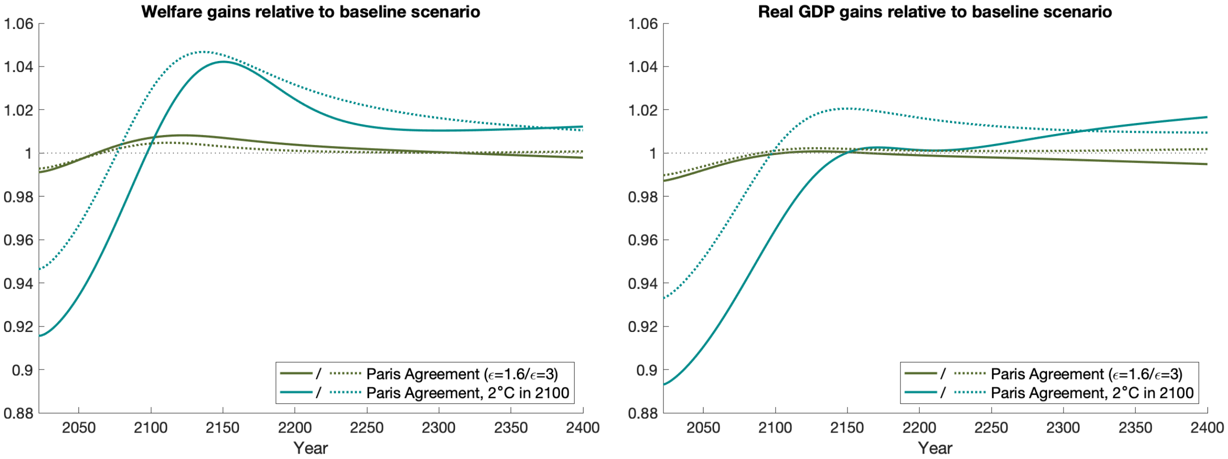

Figure 9: Welfare and real GDP gains under different warming targets and energy elasticities.

carbon (LSCC) is negative in some regions, and large and positive in others. This implies that governments and individuals across the globe will agree or disagree with this policy depending on their own LSCC (even if they fully take into account local social, and not only private, costs). We find that given the skewness in the distribution of the LSCC, a majority of people would be against a policy that simply imposes carbon taxes such that the carbon price everywhere is equal to the social cost of carbon.

Second, the level of carbon taxes that are required to achieve the Paris Agreement stated goals of increases of less than 2°C relative to pre-industrial levels are enormous. This is the case even though our baseline scenario uses an elasticity of substitution between clean and fossil fuels of 1.6, which is in line with the literature, but errs on the high side. Increasing it further to 3 helps, but still requires taxes that are on average larger than 200$ per ton of CO_2. Achieving this target with only carbon policy seems unrealistic and perhaps we need to reconsider the feasibility of the target itself.

Third, carbon taxes of the magnitude needed to achieve the Paris Agreement goals involve very large inter-temporal transfers. Something that has been recognized repeatedly in the literature. Imposing the necessary cost on current generations will be hard, even if we care deeply about future generations. The resulting welfare gains, when we value future generations almost as much as ourselves (including the effect on growth) are small, but negative for most of the developed world. They turn positive when the elasticity of substitution between energy sources is larger. Increasing this elasticity seems essential to make the required carbon policy more palatable.

Naturally, many aspects of local carbon policy are left for future research. We have talked little about uncertainty, Cruz and Rossi-Hansberg (2024) address uncertainty in the damage functions, but incorporating risk more fully is essential. Thinking more deeply about micro-foundations of the energy production function and the elasticity of substitution between energy sources based on capital accumulation is first order. Finally, we need to make progress in understanding optimal spatial carbon policy and the role the spatial distribution of the rebates from the revenues of these policies plays in affecting their welfare consequences.

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Appendix

A Proofs

Lemma 1. *The Local Social Cost of Carbon of cell r is given by,*

$$
\begin{aligned}
LSCC_t(r) &= -\left(\frac{\Delta W_t(r)[\Delta E_t^f]}{1\ tCO_2}\right) \Bigg/ \left(\frac{\Delta u_t(r)[\Delta w_t(r)]}{1\$}\right) \\
&= -\left(\frac{\Delta W_t(r)[\Delta E_t^f]}{u_t(r)}\right)\left(\frac{w_t(r)^\Lambda}{\Psi_t(r)\cdot w_t'(r)^\Lambda - w_t(r)^\Lambda}\right)\left(\frac{1\$}{1\ tCO_2}\right), \\
\Psi_t(r) &= \left(\frac{\int_S u_t(v)^{1/\Omega} m_2(v)^{-1/\Omega}\,\mathrm{d}v}{u_t(r)^{1/\Omega} m_2(r)^{-1/\Omega}\left[\left(w_t'(r)/w_t(r)\right)^{\Lambda/\Omega} - 1\right] + \int_S u_t(v)^{1/\Omega} m_2(v)^{-1/\Omega}\,\mathrm{d}v}\right)^{\varkappa/\theta},
\end{aligned}
$$

where $w_t'(r) = w_t(r) + 1\ \$$, $\Lambda = (1+2\theta)/(\theta - \varkappa/\Omega)$, *and* $\varkappa = \alpha - 1 + \theta(\lambda + \gamma_1/\xi - (1-\mu))$.

Consider equations (3) and (66) from Cruz and Rossi-Hansberg (2024),

$$
\begin{aligned}
w_t(r)^{1+2\theta} &= f_1 \bar{a}_t(r) L_t(r)^{-\varkappa} \mathcal{Q}_t(r)^{-(1-\chi)\mu\theta} H(r)^{-1} \bar{b}_t(r)^{-\theta} u_t(r)^{\theta}, \\
L_t(r) &= H(r)^{-1} u_t(r)^{1/\Omega} m_2(r)^{-1/\Omega}\left(\frac{L_t}{\int_S u_t(v)^{1/\Omega} m_2(v)^{-1/\Omega}\,\mathrm{d}v}\right),
\end{aligned}
$$

where $\varkappa = \alpha - 1 + \theta(\lambda + \gamma_1/\xi - (1-\mu))$, and combine them as shown below,

$$
w_t(r)^{1+2\theta} = f_1 L_t^{-\varkappa} \bar{a}_t(r) \mathcal{Q}_t(r)^{-(1-\chi)\mu\theta} H(r)^{\varkappa-1} \bar{b}_t(r)^{-\theta} m_2(r)^{\varkappa/\Omega} u_t(r)^{\theta-\varkappa/\Omega}\left(\int_S u_t(v)^{1/\Omega} m_2(v)^{-1/\Omega}\,\mathrm{d}v\right)^{\varkappa}. \tag{3}
$$

Now, consider a counterfactual economy in which the fundamentals (i.e., productivity, amenities, land shares, energy prices, migration and trade costs) are the same, but the wage in region r is different, $w_t'(r)$,

$$
w_t'(r)^{1+2\theta} = f_1 L_t^{-\varkappa} G_t(r) u_t'(r)^{\theta-\varkappa/\Omega}\left(\int_S u_t'(v)^{1/\Omega} m_2(v)^{-1/\Omega}\,\mathrm{d}v\right)^{\varkappa}, \tag{4}
$$

where $G_t(r) = \bar{a}_t(r)\mathcal{Q}_t(r)^{-(1-\chi)\mu\theta} H(r)^{\varkappa-1}\bar{b}_t(r)^{-\theta} m_2(r)^{\varkappa/\Omega}$ and $u_t'(r)$ is utility in the counterfactual economy. Take the ratio of the counterfactual to the factual wage,

$$
\left(\frac{w_t'(r)}{w_t(r)}\right)^{1+2\theta} = \left(\frac{u_t'(r)}{u_t(r)}\right)^{\theta-\varkappa/\Omega}\left(\frac{\int_S u_t'(v)^{1/\Omega} m_2(v)^{-1/\Omega}\,\mathrm{d}v}{\int_S u_t(v)^{1/\Omega} m_2(v)^{-1/\Omega}\,\mathrm{d}v}\right)^{\varkappa}. \tag{5}
$$

Take the ratio of equation (5) of region r to that of region s,

$$\begin{aligned}\left(\frac{w'_t(r)}{w_t(r)}\Big/\frac{w'_t(s)}{w_t(s)}\right)^{1+2\theta} &= \left(\frac{u'_t(r)}{u_t(r)}\Big/\frac{u'_t(s)}{u_t(s)}\right)^{\theta-\varkappa/\Omega}, \\ u'_t(s) = u_t(s)\left(\frac{u'_t(r)}{u_t(r)}\right)&\left(\frac{w'_t(s)}{w_t(s)}\right)^{\frac{1+2\theta}{\theta-\varkappa/\Omega}}\left(\frac{w'_t(r)}{w_t(r)}\right)^{-\frac{1+2\theta}{\theta-\varkappa/\Omega}}. \qquad (6)\end{aligned}$$

Insert equation (6) into (4),

$$\begin{aligned}w'_t(r)^{1+2\theta} &= f_1 L_t^{-\varkappa} G_t(r) u'_t(r)^{\theta-\varkappa/\Omega}\left(\int_S u_t(v)^{1/\Omega}\left(\frac{u'_t(r)}{u_t(r)}\right)^{1/\Omega}\left(\frac{w'_t(v)}{w_t(v)}\right)^{\frac{1+2\theta}{\theta\Omega-\varkappa}}\left(\frac{w'_t(r)}{w_t(r)}\right)^{-\frac{1+2\theta}{\theta\Omega-\varkappa}} m_2(v)^{-1/\Omega}\,\mathrm{d}v\right)^{\varkappa} \\ &= f_1 L_t^{-\varkappa} G_t(r) u'_t(r)^{\theta} u_t(r)^{-\varkappa/\Omega}\left(\frac{w'_t(r)}{w_t(r)}\right)^{-\frac{1+2\theta}{\theta\Omega/\varkappa-1}}\left(\int_S u_t(v)^{1/\Omega}\left(\frac{w'_t(v)}{w_t(v)}\right)^{\frac{1+2\theta}{\theta\Omega-\varkappa}} m_2(v)^{-1/\Omega}\,\mathrm{d}v\right)^{\varkappa},\end{aligned}$$

and solve for $u'_t(r)$,

$$\begin{aligned}u'_t(r)^{-\theta} &= f_1 L_t^{-\varkappa} G_t(r) u_t(r)^{-\varkappa/\Omega} w'_t(r)^{-(1+2\theta)\frac{\theta}{\theta-\varkappa/\Omega}} w_t(r)^{(1+2\theta)\frac{\varkappa/\Omega}{\theta-\varkappa/\Omega}} \\ &\times\left(\int_S u_t(v)^{1/\Omega}\left(\frac{w'_t(v)}{w_t(v)}\right)^{\frac{1+2\theta}{\theta-\varkappa/\Omega}\frac{1}{\Omega}} m_2(v)^{-1/\Omega}\,\mathrm{d}v\right)^{\varkappa}. \qquad (7)\end{aligned}$$

Recall equation (3) and manipulate it as shown below,

$$f_1 L_t^{-\varkappa} G_t(r) = w_t(r)^{1+2\theta} u_t(r)^{-\theta+\varkappa/\Omega}\left(\int_S u_t(v)^{1/\Omega} m_2(v)^{-1/\Omega}\,\mathrm{d}v\right)^{-\varkappa}; \qquad (8)$$

insert equation (3) into equation (7), and define $\Lambda = \frac{1+2\theta}{\theta-\varkappa/\Omega}$,

$$\left(\frac{u'_t(r)}{u_t(r)}\right) = \left(\frac{w'_t(r)}{w_t(r)}\right)^{\Lambda}\left(\int_S u_t(v)^{1/\Omega}\left(\frac{w'_t(v)}{w_t(v)}\right)^{\Lambda/\Omega} m_2(v)^{-1/\Omega}\,\mathrm{d}v\right)^{-\varkappa/\theta}\left(\int_S u_t(v)^{1/\Omega} m_2(v)^{-1/\Omega}\,\mathrm{d}v\right)^{\varkappa/\theta}; \qquad (9)$$

since only the wage in region r is changing, then

$$\begin{aligned}\int_S u_t(v)^{1/\Omega}\left(\frac{w'_t(v)}{w_t(v)}\right)^{\Lambda/\Omega} m_2(v)^{-1/\Omega}\,\mathrm{d}v &= \mathcal{U}_t + u_t(r)^{1/\Omega} m_2(r)^{-1/\Omega}\left[\left(\frac{w'_t(r)}{w_t(r)}\right)^{\Lambda/\Omega} - 1\right] \\ \mathcal{U}_t &= \int_S u_t(v)^{1/\Omega} m_2(v)^{-1/\Omega}\,\mathrm{d}v.\end{aligned}$$

Finally, rewrite equation (9),

$$\left(\frac{u'_t(r)}{u_t(r)}\right) = \left(\frac{w'_t(r)}{w_t(r)}\right)^{\Lambda}\left(\frac{\mathcal{U}_t}{\mathcal{U}_t + u_t(r)^{1/\Omega} m_2(r)^{-1/\Omega}\left[\left(w'_t(r)/w_t(r)\right)^{\Lambda/\Omega} - 1\right]}\right)^{\varkappa/\theta}.$$

B Additional Figures and Tables

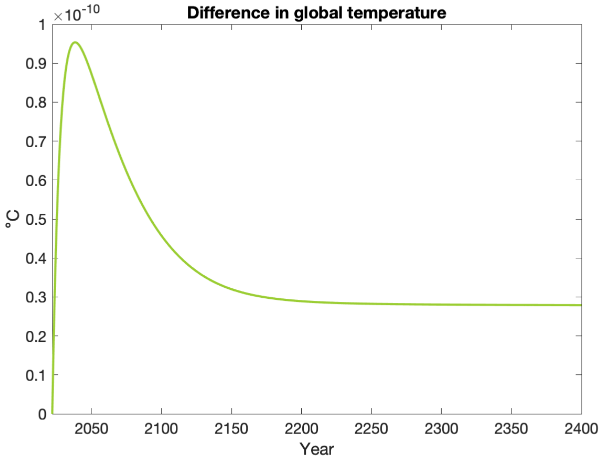


Figure 10: Change in temperature after a pulse of 100 tCO_2.

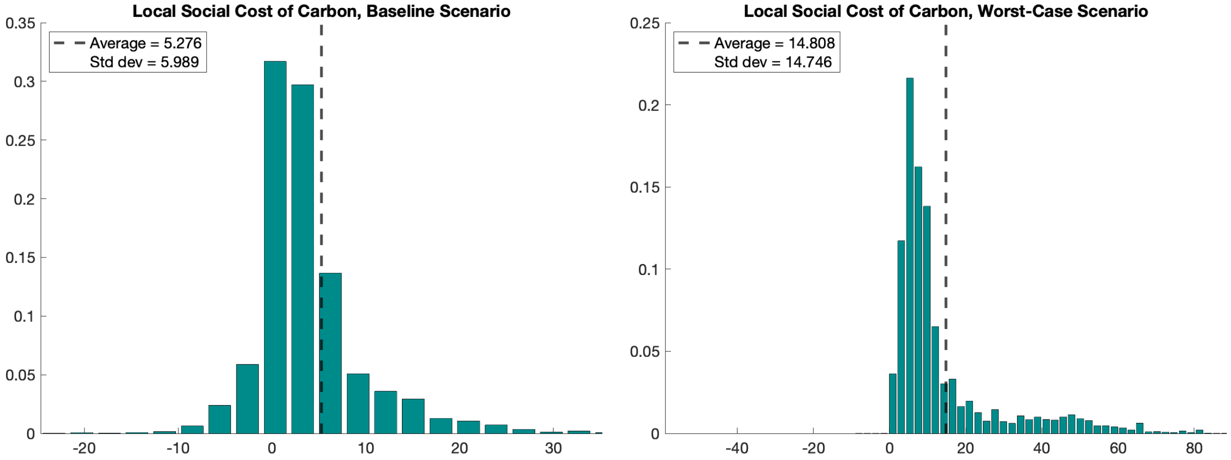


Figure 11: Distribution of Local Social Cost of Carbon in the baseline and worst-case scenario.

ISO code	Country name	Baseline Scenario		Worst-Case Scenario	
		$\beta = 0.965$	$\beta = 0.970$	$\beta = 0.965$	$\beta = 0.970$
8	Albania	3.97	49.42	14.12	103.75
12	Algeria	7.49	59.29	17.89	110.25
24	Angola	5.68	45.48	9.76	72.99
28	Antigua and Barbuda	24.58	129.89	38.87	202.98
32	Argentina	8.51	68.62	21.75	132.31
51	Armenia	-0.31	23.02	6.14	63.74
36	Australia	20.84	114.33	49.11	219.29
40	Austria	4.31	80.07	45.86	223.30
31	Azerbaijan	1.82	33.52	8.38	73.66
48	Bahrain	41.89	182.13	72.79	297.51
50	Bangladesh	3.13	34.86	5.78	57.26
112	Belarus	-0.17	31.86	12.34	92.09
56	Belgium	14.48	115.62	54.85	259.58
84	Belize	9.29	62.82	16.22	103.21
204	Benin	4.51	41.91	7.08	64.19

		Baseline Scenario		**Worst-Scenario**	
ISO code	**Country name**	$\beta = 0.965$	$\beta = 0.970$	$\beta = 0.965$	$\beta = 0.970$
64	Bhutan	1.69	29.76	7.69	65.39
68	Bolivia (Plurinational State of)	5.51	46.84	11.41	82.56
70	Bosnia and Herzegovina	1.99	39.42	12.36	93.36
72	Botswana	11.71	66.08	22.46	113.17
76	Brazil	12.41	79.18	22.06	130.37
96	Brunei Darussalam	14.94	89.00	24.66	142.69
100	Bulgaria	2.09	43.51	14.76	106.16
854	Burkina Faso	3.47	32.31	5.42	49.22
108	Burundi	1.88	22.08	3.24	35.05
116	Cambodia	3.72	36.66	6.21	58.00
120	Cameroon	5.30	43.68	8.60	68.27
124	Canada	−5.25	46.02	32.17	178.28
132	Cabo Verde	6.82	61.19	11.54	97.48
140	Central African Republic	2.59	24.81	4.16	38.35
148	Chad	2.33	23.33	3.72	35.94
152	Chile	6.01	59.96	19.75	125.45
156	China	1.67	34.75	8.52	77.79
170	Colombia	10.44	69.8	18.29	114.54
174	Comoros	4.69	48.91	7.57	75.63
178	Congo	7.67	54.21	12.37	84.61
188	Costa Rica	13.26	82.80	22.51	134.54
384	Cte d'Ivoire	5.28	43.49	8.34	67.03
191	Croatia	4.89	64.71	26.82	155.66
196	Cyprus	24.21	133.61	50.54	238.99
203	Czechia	3.09	65.98	29.72	174.20
180	Democratic Republic of the Congo	1.15	14.34	1.91	22.29
208	Denmark	9.10	95.86	49.47	237.85
262	Djibouti	4.70	42.74	7.82	67.59
214	Dominican Republic	11.07	74.59	18.61	119.91
218	Ecuador	8.67	62.95	16.47	107.25
818	Egypt	8.75	71.95	16.74	120.56
222	El Salvador	10.95	79.54	18.18	126.73
226	Equatorial Guinea	19.90	101.52	31.36	158.37
232	Eritrea	2.23	25.72	3.96	41.60
233	Estonia	0.99	48.74	21.13	135.67
231	Ethiopia	1.68	21.50	3.18	35.59
583	Micronesia (Fed. States of)	9.40	77.96	14.94	120.58
242	Fiji	8.77	66.13	14.78	105.88
246	Finland	−3.81	47.51	33.43	176.79
250	France	15.52	112.04	52.43	242.48
266	Gabon	21.66	102.97	33.97	160.31
270	Gambia	4.10	38.91	6.97	62.20
276	Germany	9.03	96.23	49.77	238.81
288	Ghana	3.86	36.97	6.09	56.72
300	Greece	14.67	99.50	40.32	200.38
304	Greenland	−13.69	21.92	32.76	161.27
308	Grenada	12.02	85.28	21.23	140.84
320	Guatemala	7.37	59.03	13.64	98.93
324	Guinea	2.90	29.02	4.80	45.62
624	Guinea-Bissau	1.91	22.75	3.28	36.25
328	Guyana	5.70	46.24	9.81	75.00
332	Haiti	3.95	40.02	6.58	63.06
340	Honduras	6.12	50.59	10.92	83.19
348	Hungary	3.30	61.65	26.43	158.03
352	Iceland	3.10	68.91	40.82	197.23
356	India	4.87	45.82	8.71	74.64
360	Indonesia	7.36	58.74	11.96	92.10
364	Iran (Islamic Republic of)	4.98	52.00	18.23	112.57
372	Ireland	19.53	119.99	58.65	250.44
376	Israel	23.39	128.85	49.84	232.78
380	Italy	15.28	109.06	48.89	231.48
388	Jamaica	13.77	91.63	22.40	144.75
392	Japan	14.85	111.64	52.08	244.73
400	Jordan	6.04	52.54	14.09	96.13
398	Kazakhstan	−3.16	16.42	8.07	71.39
404	Kenya	3.58	34.99	6.27	56.25
296	Kiribati	7.04	58.90	10.85	89.42

		Baseline Scenario		Worst-Scenario	
ISO code	**Country name**	$\beta = 0.965$	$\beta = 0.970$	$\beta = 0.965$	$\beta = 0.970$
368	Iraq	31.91	147.42	61.49	254.08
417	Kyrgyzstan	−1.16	13.32	3.71	45.70
418	Lao People's Democratic Republic	3.40	33.78	6.32	56.13
428	Latvia	0.73	41.21	17.02	114.15
422	Lebanon	10.43	80.69	24.60	150.25
426	Lesotho	1.86	26.54	5.37	51.42
430	Liberia	1.84	21.86	3.01	33.91
440	Lithuania	0.75	42.58	18.25	118.68
807	North Macedonia	2.72	45.40	16.56	109.19
450	Madagascar	2.79	29.8	5.00	48.22
454	Malawi	2.29	25.41	4.00	40.62
458	Malaysia	17.31	96.94	27.98	153.54
462	Maldives	8.84	71.12	14.38	111.79
466	Mali	3.08	28.76	4.90	44.26
470	Malta	23.60	148.76	51.06	269.56
478	Mauritania	4.81	38.71	7.77	60.13
480	Mauritius	17.62	113.19	29.93	182.29
484	Mexico	12.26	81.16	26.43	147.02
498	Republic of Moldova	0.47	28.63	8.00	73.29
496	Mongolia	−3.31	3.64	2.50	39.56
504	Morocco	5.20	48.93	11.57	87.59
508	Mozambique	1.96	22.66	3.38	35.94
104	Myanmar	1.92	24.70	3.56	40.58
516	Namibia	7.16	49.20	13.25	81.95
524	Nepal	1.87	26.14	4.65	48.05
528	Netherlands	15.52	124.50	59.86	281.94
554	New Zealand	15.22	99.55	40.01	197.22
558	Nicaragua	5.57	48.06	9.34	76.62
562	Niger	2.18	23.13	3.56	35.86
566	Nigeria	4.67	41.59	7.45	64.21
578	Norway	2.44	75.53	50.89	230.32
512	Oman	26.41	116.21	43.39	184.47
586	Pakistan	4.95	47.80	9.72	80.73
591	Panama	13.56	86.21	22.90	139.77
598	Papua New Guinea	4.07	37.54	7.42	62.11
600	Paraguay	7.58	58.09	13.97	96.61
604	Peru	7.30	58.65	15.52	104.69
608	Philippines	5.76	52.69	10.28	86.55
616	Poland	2.01	52.88	22.18	139.75
620	Portugal	20.32	121.15	46.02	223.97
642	Romania	1.23	41.35	14.59	106.93
643	Russian Federation	−4.40	22.99	12.05	99.21
646	Rwanda	2.17	25.62	3.93	41.67
882	Samoa	15.67	98.07	20.27	131.52
682	Saudi Arabia	21.11	95.59	36.98	156.50
686	Senegal	4.36	42.64	7.34	67.66
688	Serbia	2.30	46.81	16.77	115.30
690	Seychelles	31.21	152.21	48.80	235.82
694	Sierra Leone	1.59	20.04	2.65	31.35
702	Singapore	18.56	106.64	28.95	165.00
703	Slovakia	2.48	57.75	25.14	152.24
705	Slovenia	3.27	69.35	36.50	191.29
90	Solomon Islands	6.54	53.00	10.37	81.94
710	South Africa	9.11	66.63	19.92	119.96
410	Republic of Korea	3.77	72.89	32.60	190.06
724	Spain	19.70	119.98	50.17	233.23
144	Sri Lanka	7.69	61.80	12.71	98.00
659	St Kitts and Nevis	22.28	119.93	35.23	187.53
662	St Lucia	13.56	93.91	23.94	155.32
670	St Vincent and the Grenadines	10.43	80.79	18.52	133.32
729	Sudan	3.91	33.86	6.38	52.92
740	Suriname	11.21	69.34	17.68	107.88
748	Eswatini	7.25	55.43	14.12	94.67
752	Sweden	2.50	70.54	41.06	204.46
756	Switzerland	6.18	88.69	48.54	236.26
760	Syrian Arab Republic	4.62	44.95	12.22	86.00
762	Tajikistan	0.59	19.81	4.04	45.46

		Baseline Scenario		**Worst-Scenario**	
ISO code	**Country name**	$\beta = 0.965$	$\beta = 0.970$	$\beta = 0.965$	$\beta = 0.970$
834	United Republic of Tanzania	2.94	30.40	5.00	48.14
764	Thailand	9.88	66.47	16.47	106.50
768	Togo	3.30	32.22	5.15	49.12
776	Tonga	11.20	81.97	16.80	122.21
780	Trinidad and Tobago	18.04	100.12	31.62	166.46
788	Tunisia	7.91	62.69	17.54	112.88
792	Turkey	5.13	58.41	20.55	129.49
800	Uganda	2.95	30.75	4.85	47.95
804	Ukraine	0.11	30.89	9.42	83.43
784	United Arab Emirates	47.63	174.64	79.01	279.11
826	United Kingdom	15.60	114.63	53.54	249.16
840	United States of America	13.51	101.10	53.04	235.11
858	Uruguay	8.66	67.47	21.50	128.87
860	Uzbekistan	0.82	24.42	5.59	56.76
548	Vanuatu	9.72	69.26	15.28	106.46
862	Venezuela (Bolivarian Republic of)	15.08	88.39	24.99	141.80
704	Viet Nam	4.15	43.21	7.74	71.95
887	Yemen	4.88	40.88	8.58	66.41
894	Zambia	2.57	26.80	4.63	43.53

Table 5: Local Social Cost of Carbon by country for the baseline and worst-case scenario and for different discount factors.

Region	**Carbon Tax** *($/$tCO_2$)*	**Δ%CO$_2$** **Own**	**RoW**	**Δ%Real GDP** **Own**	**RoW**
Asia Pacific	6.10	-8.83	-0.02	-1.13	0.05
China	11.86	-22.88	0.78	-2.94	0.29
East Europe and Central Asia	3.74	-10.56	0.04	-1.29	0.02
Latin America and Caribbean	4.55	-6.07	-0.01	-0.57	0.02
Middle East and North Africa	0	0	0	0	0
North America	6.82	-38.09	-0.34	-4.04	0.05
South Asia	0	0	0	0	0
Sub Saharan Africa	47.36	-13.54	0.15	-1.64	0.08
Europe	8.68	-23.21	-0.33	-2.17	0.05

Table 6: Unilateral carbon taxes to achieve the Paris Agreement pledges, $\epsilon = 3$.

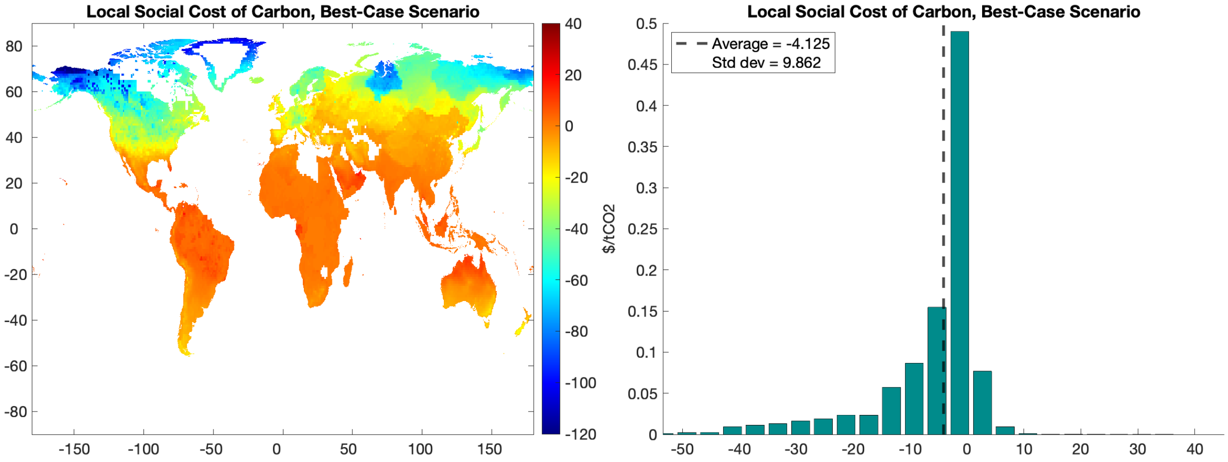


Figure 12: Local Social Cost of Carbon in the best scenario.

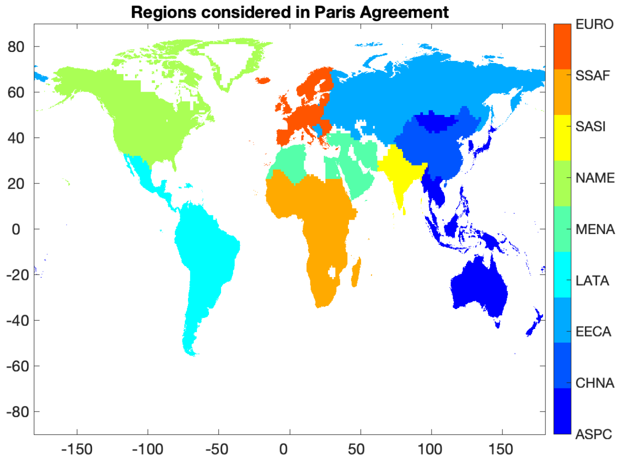


Figure 13: Definition of regions.

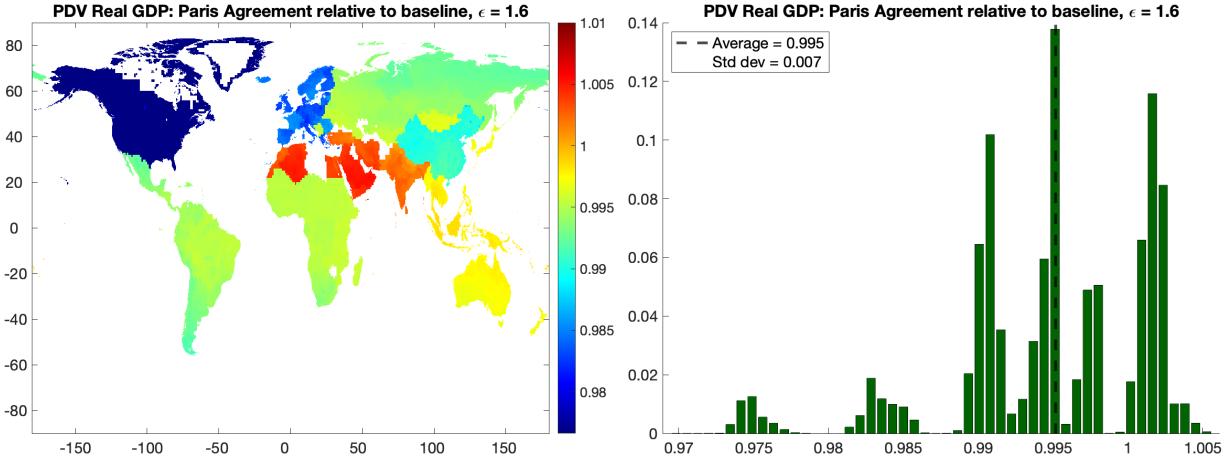
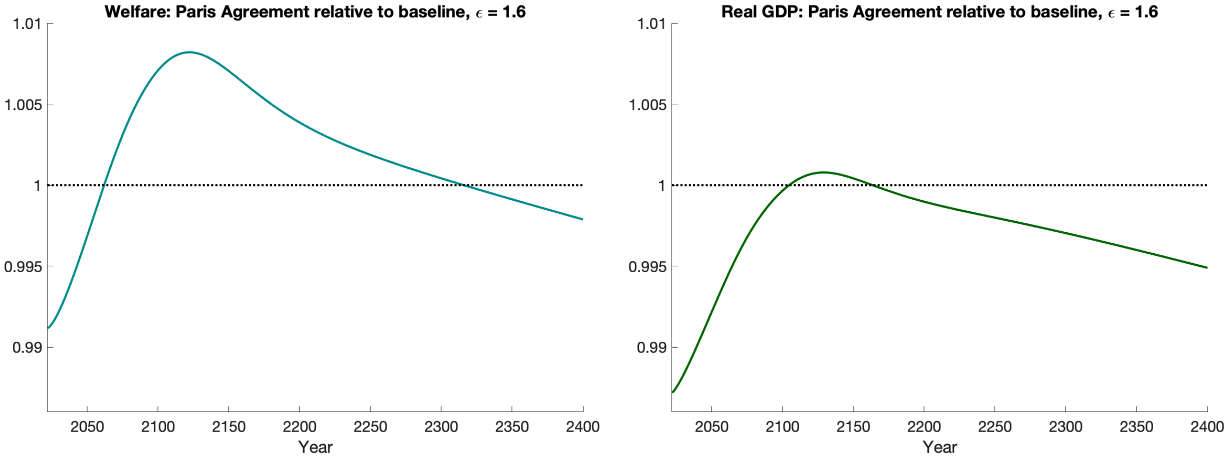


Figure 14: Real GDP gains under the Paris Agreement.



Welfare: Paris Agreement relative to baseline, ϵ = 1.6

Real GDP: Paris Agreement relative to baseline, ϵ = 1.6

Figure 15: Dynamic global welfare and real GDP gains under the Paris Agreement.

Region	**PDV Real GDP**			
	$\epsilon = 1.6$		$\epsilon = 3$	
	2050	2100	2050	2100
Asia Pacific	0.9934	0.9802	0.9988	0.9978
China	0.9894	0.9769	0.9959	0.9949
East Europe and Central Asia	0.9901	0.9665	0.9963	0.9882
Latin America and Caribbean	0.9907	0.9752	1.0007	1.0061
Middle East and North Africa	0.9894	0.9701	0.9998	0.9794
North America	0.9693	0.9429	0.9876	0.9860
South Asia	0.9990	0.9917	1.0023	1.0036
Sub Saharan Africa	0.9945	0.9956	1.0023	1.0112
Europe	0.9780	0.9538	0.9937	0.9929
Global Average	**0.9916**	**0.9799**	**0.9988**	**0.9989**

Table 7: PDV Real GDP gains from imposing the carbon taxes necessary to stay below the 2°C target with the Paris Agreement regional distribution.