Climate Change Impact on Economic Growth: Regional Climate Policy under Cooperation and Noncooperation

Yongyang Cai, William Brock, Anastasios Xepapadeas

Abstract: We develop a novel analysis of climate change and policy regarding climate damages to growth under regional cooperation or noncooperation. We introduce a new stylized climate module and compute the regional social cost of carbon (SCC) when climate change impacts the growth rate of regional GDP under cooperation and noncooperation between regions. We find that in the presence of climate damage to economic growth, the regional SCC is high in either a cooperative or a noncooperative world, implying that it is optimal for each region to choose stringent climate policies. Moreover, relative to cooperation, noncooperation reduces the GDP of countries in both high northern latitudes and the tropics, while the loss for developing countries in the tropics is especially significant. The welfare losses to the tropics are larger still in the absence of compensatory transfers from wealthier regions most responsible for climate change.

JEL Codes: Q54, Q58

Keywords: integrated assessment model of climate and economy, spatial heat transport, regional social cost of carbon, carbon tax, Nash equilibrium, economic growth

WE BEGIN WITH A SHORT PREVIEW of the three main contributions of our paper before turning to a review of the literature. One major finding of this paper is that in

Yongyang Cai is at the Department of Agricultural, Environmental and Development Economics, Ohio State University (cai.619@osu.edu). William Brock is at the Department of Economics, University of Wisconsin–Madison, and University of Missouri–Columbia (wbrock@ssc.wisc.edu). Anastasios Xepapadeas is at the Department of International and European Economic Studies, Athens University of Economics and Business, and Department of Economics, University of Bologna (xepapad@aueb.gr). We thank the coeditor of this journal, Simon Dietz, and two anonymous

Dataverse data: https://doi.org/10.7910/DVN/PWMQJ7

Received December 7, 2020; Accepted August 16, 2022; Published online March 22, 2023.

Journal of the Association of Environmental and Resource Economists, volume 10, number 3, May 2023.

https://doi.org/10.1086/722274

the presence of climate damage to economic growth,[1] the regional social cost of carbon (SCC) is high for either a cooperative world (modeled as world social welfare optimization) or a noncooperative world (modeled as an open-loop Nash equilibrium). Unlike much of the climate economics literature considering world social welfare optimization, we do not allow compensatory income and wealth transfers across regions. We believe such compensatory transfers are unrealistic. In our baseline case, under cooperation the initial regional SCC is \$806/tCO_2 (per ton of carbon dioxide) for the high northern latitude region, and \$117/tCO_2 for the tropical region, while under noncooperation the numbers become \$49/tCO_2 and \$137/tCO_2 for the high northern latitude region and the tropical region, respectively.[2] These numbers tell us that under either cooperation or noncooperation it is always optimal for each region to choose stringent climate policies. Moreover, in the baseline case, it is optimal for each region to keep the global mean atmospheric temperature anomaly in this century below 1.5°C under cooperation, or below 2°C under noncooperation. These conclusions are robust in our other five major cases.

The second interesting finding of this study is that the regional SCC for the developed countries in the high northern latitudes is higher than for the developing countries in the tropical region in a cooperative world, although climate change has little impact on the economic growth of many countries in the high northern latitudes in this century. This is because consumption in the developing countries in the tropical region has higher marginal utility than in the developed countries in the northern region. The social welfare planner wishes to maximize total utility and thus tries to equate marginal utilities across regions. The planner would like to transfer additional income or wealth across regions for each gigaton of carbon emitted, especially from rich regions to poor regions that are harmed more by climate change. But since direct transfers of income and wealth across regions are shut down, the social planner uses differentiated carbon taxes to achieve some second-best redistribution. That is, this constraint on income or wealth transfers raises the marginal damage to the whole world from emitting a gigaton of carbon anywhere. Hence SCCs will be increased over the case where income/wealth transfers are allowed, and SCCs in the nontropics will be increased a lot because reduction of nontropics emissions has a lower utility cost than that of the tropics.

However, we find that relative to cooperation, noncooperation causes little extra loss of GDP in the developed countries in the high northern latitudes but leads to

---

referees for valuable comments and suggestions. We are grateful to Rick van der Ploeg and participants at the 2021 annual conference of the European Association of Environmental and Resource Economists and the 2021 annual meeting of the Institute for Operations Research and the Management Sciences for their comments. Cai and Brock acknowledge support from the National Science Foundation grant SES-1463644.

1. Economic growth in this paper means the growth of gross domestic product (GDP).

2. We use US dollars (\$) per ton of carbon dioxide as the unit of the SCC in this paper. The SCC per ton of CO_2 equals 12/44 times the SCC per ton of carbon.

significant loss for the developing countries in the tropical region. In our baseline case, noncooperation causes an extra 3.1% loss of output (i.e., $2,393 per capita) in the northern region in 2100, relative to cooperation. But noncooperation reduces output by an extra 20% (i.e., $6,907 per capita) in the tropics in 2100. In such a noncooperative world, the northern region has a much smaller SCC, and at the same time, the regional SCC for the tropics has no significant difference between cooperation and noncooperation. The noncooperative SCC is higher than the cooperative SCC in the tropics in some cases. This is because climate change causes little impact in the northern region but it causes severe damage in the tropics. The resulting higher emissions in the northern region mean the poor tropics are induced to set carbon prices higher. The initially poor and hot countries are made even poorer by severe climate change, which is driven by the selfish policies of the developed countries in the high northern latitudes in the noncooperative solution compared to the cooperative solution.

The third interesting finding of this study is that if we model the climate change effect on the growth rate of total factor productivity (TFP), then it will significantly increase the SCC in comparison to the 10-year lagged effect of climate change on TFP levels, even when we use the same GDP scenarios to calibrate the TFP models. This tells us that we should pay attention to the specification of climate damages.

One major uncertainty in climate change economics is how much damage to an economy climate change will impose. DICE (Nordhaus 2008, 2017) uses a quadratic damage function and projects that the damage to instantaneous output will be 7.8% or 25.4% if global average atmospheric temperature increases 6°C or 12°C, respectively, over the preindustrial level. Since DICE assumes a perfect foresight dynamic model using a quadratic damage function, it provides a relatively low SCC. Weitzman (2012) points out that DICE significantly underestimates catastrophic climate damage. He changes the quadratic damage function by adding a new term: a power function of temperature increase with the exponent 6.754. The coefficient of the additional term is very small so that it has almost no impact on damage when temperature increase is lower than 2°C, but it leads to 50% or 99% damage to output if temperature increase is 6°C or 12°C, respectively, and thus it implies a significantly higher SCC.[3]

In addition to climate damage to instantaneous output, researchers also find some evidence that climate change can reduce economic growth. Evidence indicates that there are large and negative effects of higher temperatures on growth in poor countries in low-latitude regions. Dell et al. (2012) find an ~1.3% reduction in economic growth for a 1°C increase in global temperature, while Moore and Diaz (2015) and Dietz and Stern (2015) find that if climate damage reduces economic growth then the global SCC increases significantly. Rezai et al. (2018) show that climate damage to economic growth leads to a dystopian income distribution if no climate policy is imposed. Diffenbaugh and Burke (2019) show that global warming increases economic inequality, as it reduces annual economic growth in hotter and poorer countries but increases it in many

3. Dietz and Stern (2015) apply Weitzman's (2012) damage function to show this.

cooler and wealthier countries relative to a world without anthropogenic warming. However, they do not analyze regional scale issues under the richer and more detailed climate dynamics that we have here.[4] Ueckerdt et al. (2019) combine estimates of climate change impacts on economic growth for 186 countries and find that the global warming limit that minimizes this century's total economic costs of climate change lies between 1.9°C and 2°C.

Empirical findings in the literature are still ambiguous about whether global warming reduces instantaneous output or economic growth. For example, Dell et al. (2012) show that the effects of temperature persist for 10–15 years in poor countries. Burke et al. (2015b) and Burke et al. (2018) find that global warming impacts economic growth, leading to higher income in the high northern latitudes but significant loss in the tropical region. Kalkuhl and Wenz (2020) find that temperature affects productivity levels considerably, but there is no evidence of its impact on permanent growth rates if nonmarket impacts and costs due to sea level rise are excluded. Kahn et al. (2021) argue that all regions (cold or hot, and rich or poor) will experience a relatively large fall in GDP per capita by 2100 if there are no climate policies.[5]

Our model follows recent research work and assumes that the temperature anomaly affects economic growth, by modeling it with climate impact on the growth rate of TFP or 10-year lagged climate impact on TFP levels. We calibrate climate impact using the projection GDP data of Burke et al. (2018). The model also incorporates heat transfer from low latitudes to high latitudes and polar amplification, which means that warming in the high latitudes increases faster than in the tropical region. Our results are in line with recent findings, suggesting that damages from temperature increase at low latitudes are much higher than at high latitudes.[6]

Almost every integrated assessment model (IAM) (e.g., DICE) uses a social planner model assuming that countries are unselfish and the social planner can allocate resources between countries without any border friction. But if we have multiple regions in a model, then under social welfare optimization this "unselfish region" assumption will lead to extremely large capital flows between regions (from rich regions to poor regions), as discussed in the pure Negishi solution in Nordhaus and Yang (1996). One way to avoid unrealistic compensatory income or wealth transfers between regions is to impose border frictions as in Cai et al. (2019). In this paper, for simplicity we assume

4. The literature also discusses the SCC under uncertainties of climate damage. See, e.g., Cai et al. (2016), Cai et al. (2017), Cai and Lontzek (2019), Barnett et al. (2020), Dietz, Rising, et al. (2021), and the recent review article by Cai (2021).

5. See Carleton and Hsiang (2016), Heal and Park (2016), Auffhammer (2018), Kolstad and Moore (2020), Neumann et al. (2020), and Cai (2021) for more discussion about the climate impact on output levels and growth rates.

6. See, e.g., Meinshausen, Raper, et al. (2011), Burke et al. (2015b), Dennig et al. (2015), Hsiang et al. (2017), Burke et al. (2018), and Kalkuhl and Wenz (2020).

that the regional economy is closed, so there is no capital flow between regions (but for each region, the social planner can allocate resources between countries inside the region without any border friction). That is, cooperation between regions in our social planner's problem happens only on climate change mitigation (which will of course affect consumption and capital investment). But this is a solution of the extreme case.

In this paper, besides this social planner's solution, we also provide an open-loop Nash equilibrium solution in the other extreme case when regions are noncooperative and maximize own utility only taking into account climate change damages to their own output. Climate policy under cooperation and noncooperation between regions has been studied in the literature. For example, Dutta and Radner (2009) have a theoretical analysis of a dynamic commons game for modeling the global warming process, in which the players are countries. RICE (Nordhaus 2010) studies the regional SCC under a social planner's model with weights on regional utilities, so it does not study noncooperative outcomes.[7] Van der Ploeg and de Zeeuw (2016) and Jaakkola and van der Ploeg (2019) study tipping points without geographical regional specification and poleward heat transport. Brock and Xepapadeas (2019) include heat transport and regional specification, but they use a very simplified climate model without multilayer modeling of the carbon cycle and focus on the Northern Hemisphere only. Moreover, van der Ploeg and de Zeeuw (2016), Brock and Xepapadeas (2019), and Jaakkola and van der Ploeg (2019) use continuous time models and solve the associated Hamilton-Jacobi-Bellman equations or Hamiltonian systems. Cai et al. (2019) build a dynamic stochastic IAM with two regions to solve the optimal regional carbon taxes under cooperation and feedback Nash equilibrium with heat transport, sea level rise, permafrost thawing, adaptation, and climate tipping risks. They find that optimal regional carbon taxes in the high northern latitude region are higher than in the tropical region in both cooperative and noncooperative worlds. Hambel et al. (2021) provide analytical formulas for the SCC and optimal carbon taxes with international trade in a noncooperative world.

However, none of these papers account for climate damages to the rate of growth of regional GDP. Our results show very different patterns of climate policy relative to the other papers mentioned. For example, we find that cooperation under damages to the rate of growth of regional GDP does not lead to converging carbon taxes for the regions as shown in van der Ploeg and de Zeeuw (2016). This is particularly because we calibrate our climate-impacted TFP models with the recent empirical work of Burke et al. (2018), which shows strongly asymmetric damages from climate change in the regions: the tropical region suffers severe climate damages, while the high northern latitude region has a little damage only.

7. However, an earlier version of RICE (Nordhaus and Yang 1996) does study noncooperative equilibria and compares with the cooperative case. To our knowledge, none of the RICE-type models has heat transport or climate damage to economic growth as does our model.

The paper is organized as follows. Section 1 describes our model while some details are provided in the appendices. Section 2 discusses cooperation and noncooperation. Section 3 shows our numerical results, including the comparison of the regional SCC between the regions, between two specifications of climate damage (damage to TFP growth vs. damage to TFP levels), and between three GDP projection scenarios. Section 4 concludes.

1. MODEL SETUP

There are two main ways to partition the globe into multiple regions in an IAM. One way is to follow political and legal jurisdictions, but this can only provide a rough approximation of the regional climate systems. For example, the RICE model (Nordhaus 2010)—the regional version of DICE (Nordhaus 2017)—treats the climate system by using the globally averaged measure of temperature and neglects heat and moisture transport and especially polar amplification. Hassler and Krusell (2012) extend Golosov et al. (2014) to multiregions. While their work is elegant, as is that of Golosov et al. (2014), they do not deal with poleward heat transport, multilayer carbon cycles, and separation of atmospheric and oceanic layers, as we do here. Another way to partition the globe is to follow physical laws in modeling the regional climate systems (i.e., heat and moisture transfer between regions), but the regions may not have strong political and legal jurisdictions. For example, Langen and Alexeev (2007) build a general circulation model with two regions: the region from latitude 30°N to 90°N, and the region from latitude 0°N to 30°N.

In this study, we define three regions over the globe for the temperature system: the North is the region from 30°N to 90°N (indexed as region 1), the Tropics is the region from 30°S to 30°N (indexed as region 2),[8] and the South is the region from 90°S (the South Pole) to 30°S (indexed as region 3). The directionalities of heat and moisture transport are toward the North and the South from the Tropics (see Wunsch 2005, fig. 1). For the economic system, since the South has a relatively small amount of economic activity, we merge it with the Tropics and name it the Tropics/South (also indexed as region 2 for economic variables only for convenience). That is, we have two economic regions while our climate system has three regions. The disaggregation in these regions not only keeps track of the significant difference of their temperature systems but also makes clear their significant economic difference since most countries in the Tropics/South are poor and more vulnerable to climate change and most countries in the North are rich and less vulnerable. The parameter values are provided in appendix A3. The structure of our model is depicted in figure 1.

---

8. Our tropical region is a bit wider than the standard definition of the tropics in geography, i.e. [23.5°S, 23.5°N], in order to balance with economic variables and to follow Langen and Alexeev (2007) for the heat transfer system.

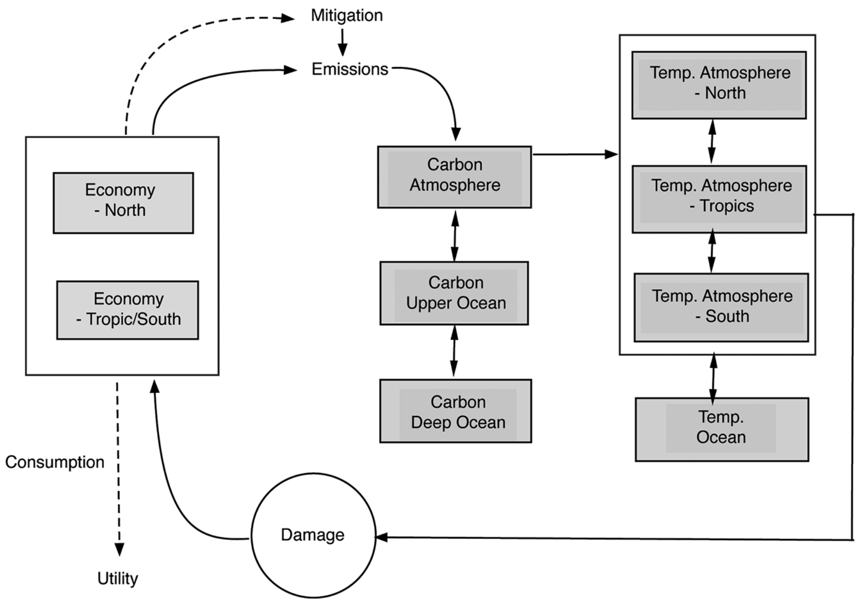

Figure 1. Schematic of our model. Under cooperation, the forward-looking social planner chooses mitigation and consumption in every economic region to maximize the sum of discounted regional utilities across economic regions over time. Regional warming impacts the economic growth in both the North and Tropics/South regions. Under noncooperation, each economic region's decision maker chooses their regional mitigation and consumption to maximize the sum of discounted utilities of their own region over time.

The economic module is based on a two-region differentiation of DICE-2016 (Nordhaus 2017). Krusell and Smith (2017) compare the two market structures of complete autarky and full international borrowing and lending and find that the market structures do not have a large impact on their results. We have ignored serious modeling of market structure in order to focus on some elements of geophysics that are ignored in other contributions, including that of Krusell and Smith (2017).

Desmet and Rossi-Hansberg (2015) and Desmet et al. (2021) suggest that labor mobility can dampen the costs of global warming. Here we assume that labor mobility is exogenous and has already been addressed in the projection of populations in the economic regions. In our model we also ignore capital transfer between the economic regions for a more consistent comparison of solutions between cooperation and noncooperation, as noncooperation leads to no capital transfer (Cai et al. 2019). But inside each economic region there is no restriction on labor mobility or capital transfer as we assume countries inside one economic region are cooperative. We impose the constraint that there is no transfer of physical consumption or investment goods between the regions in order to prevent the social planner from equalizing incomes between the two regions, as global income redistribution would distract from the main questions of mitigation of climate change.

1.1. Climate System

The climate system contains two modules: a carbon cycle and a temperature subsystem. Recently a "transient climate response to emissions" (TCRE) scheme has been employed for economic analysis (e.g., Brock and Xepapadeas 2017; van der Ploeg 2018; Dietz and Venmans 2019; Mattauch et al. 2020; Dietz, van der Ploeg, et al. 2021). The TCRE scheme assumes that contemporaneous globally or even regionally average atmospheric temperature increase is nearly linearly proportional to cumulative carbon emissions (Matthews et al. 2009; Leduc et al. 2016). However, Dietz, van der Ploeg, et al. (2021, fig. 5) show that DICE-2016R's (Nordhaus 2017) climate system does not lead to a large bias compared to the TCRE scheme using the welfare maximization criterion and DICE-2016R's economic system. Moreover, our climate system can be extended to study the impact of non-CO_2 radiative forcing, sea level rise, and solar engineering (a technology reflecting a small fraction of sunlight back into space or increasing the amount of solar radiation that escapes back into space to cool the planet).

We follow DICE-2016R (Nordhaus, 2017) in using three layers of carbon concentrations: atmospheric carbon, carbon in the upper ocean, and carbon in the deep ocean, which we denote as $\mathbf{M}_t = (M_t^{\mathrm{AT}}, M_t^{\mathrm{UO}}, M_t^{\mathrm{DO}})^\top$, respectively. The carbon cycle dynamics can be written as follows:

$$\mathbf{M}_{t+1} = \mathbf{\Phi}_{\mathrm{M}}\mathbf{M}_t + (E_t, 0, 0)^\top, \tag{1}$$

where E_t is the global carbon emission (billions of metric tons) and $\mathbf{\Phi}_{\mathrm{M}}$ is the transition matrix calibrated against four representative concentration pathways (RCP) scenarios, that is, RCP2.6, RCP4.5, RCP6, and RCP8.5 (Meinshausen, Smith, et al. 2011). See appendix A1 for more details.

The global radiative forcing represents the impact of CO_2 concentrations on the energy balance of the globe (watts per square meter from 1900) and also includes the non-CO_2 radiative forcing. We follow DICE-2016R to let the global radiative forcing be

$$F_t = \eta \log_2\left(M_t^{\mathrm{AT}}/M_*^{\mathrm{AT}}\right) + F_t^{\mathrm{EX}}, \tag{2}$$

where $\eta = 3.68$ and F_t^{EX} is the exogenous global non-CO_2 radiative forcing as in DICE-2016R.

We use $(T_{t,1}^{\mathrm{AT}}, T_{t,2}^{\mathrm{AT}}, T_{t,3}^{\mathrm{AT}}, T_t^{\mathrm{OC}})$ to represent the temperature anomaly (relative to 1900 levels) in the atmosphere of the three regions, the North, the Tropics, and the South, and the global ocean, respectively. Thus, the temperature system is

$$T_{t+1,1}^{AT} = (1 - \xi_5)T_{t,1}^{AT} - \xi_2\left(T_{t,1}^{AT} - T_t^{OC}\right) + \xi_4\left(T_{t,2}^{AT} - T_{t,1}^{AT}\right) + (\xi_1 + \xi_6)F_t, \quad (3)$$

$$\begin{aligned} T_{t+1,2}^{AT} = {} & (1 - \xi_5)T_{t,2}^{AT} - \xi_2\left(T_{t,2}^{AT} - T_t^{OC}\right) - \frac{\xi_4}{2}\left(T_{t,2}^{AT} - T_{t,1}^{AT}\right) \\ & - \frac{\xi_4}{2}\left(T_{t,2}^{AT} - T_{t,3}^{AT}\right) + (\xi_1 + \xi_7)F_t, \end{aligned} \quad (4)$$

$$T_{t+1,3}^{AT} = (1 - \xi_5)T_{t,3}^{AT} - \xi_2\left(T_{t,3}^{AT} - T_t^{OC}\right) + \xi_4\left(T_{t,2}^{AT} - T_{t,3}^{AT}\right) + \xi_1 F_t, \quad (5)$$

$$T_{t+1}^{OC} = T_t^{OC} + \xi_3\left(T_{t,1}^{AT} - T_t^{OC}\right) + 2\xi_3\left(T_{t,2}^{AT} - T_t^{OC}\right) + \xi_3\left(T_{t,3}^{AT} - T_t^{OC}\right). \quad (6)$$

Here the parameter ξ_1 is the temperature increase for each unit of radiative forcing when there is no change in climate feedback, ξ_2 and ξ_3 represent additional heat transport between atmosphere and ocean due to temperature anomalies,[9] ξ_4 is used to capture additional spatial heat and moisture transport between the North/South and the Tropics due to temperature anomalies, ξ_5 represents the sensitivity of the outgoing long-wave radiation to atmospheric temperature changes, and ξ_6 and ξ_7 are used to approximate the aggregate effect of all asymmetric climate properties through the asymmetric impact of radiative forcing. Since the area size of the Tropics is twice that of the North or the South, the parameter ξ_4 is divided by two in the Tropics' transition equation (4), and ξ_3 is multiplied by two for the difference between the Tropics' atmospheric temperature anomaly and the ocean temperature anomaly in the ocean's transition equation (6). Moreover the global mean atmospheric temperature anomaly is $(T_{t,1}^{AT} + 2T_{t,2}^{AT} + T_{t,3}^{AT})/4$.

We calibrate $\xi_1, \xi_2, \dots, \xi_7$ against the ensemble mean of CMIP5 (Navarro-Racines et al. 2020) models' annual projections of temperature anomaly in every region under the four RCP scenarios until 2100. That is, we solve the following minimization problem:

$$\min_{\xi_1,\dots,\xi_7} \sum_{j=1}^{4}\sum_{t=0}^{85}\left(\sum_{i=1}^{3}\left|T_{t,i}^{AT,j} - T_{t,i}^{CMIP5,AT,j}\right| + \left|T_{t,i}^{OC,j} - T_{t,i}^{CMIP5,OC,j}\right|\right),$$

subject to the transition equations (3)–(6) for each RCP scenario $j = 1, \dots, 4$ (represented in the superscript) over the 85-year time horizon (from the initial year 2015 to 2100), and an additional constraint $\xi_6 = (\xi_1 + (\xi_6 + 2\xi_7)/4)\eta/\xi_{ECS}$ such that our system's long-run global mean atmospheric temperature increase with a doubling of atmospheric carbon concentration is ξ_{ECS}, also known as the equilibrium climate sensitivity,

9. Heat transport under no temperature anomalies has already been normalized to be zero, so for convenience we just use "heat transport" or "heat transfer" to represent the additional heat transport due to temperature anomalies.

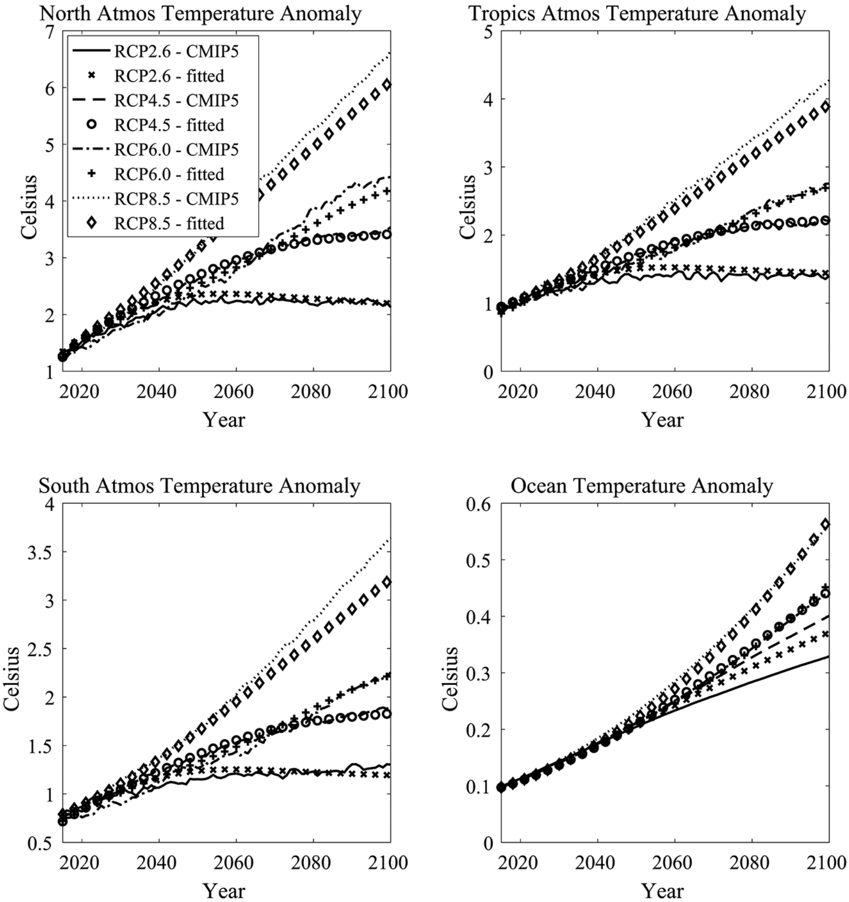

Figure 2. Fitting regional temperature anomaly under four representative concentration pathways (RCP) scenarios.

whose value is chosen to be 3.1 by following DICE-2016R.[10] Here the superscript "CMIP5" represents the data of the ensemble mean of the CMIP5 models' annual projections, and the global radiative forcing F_t for each RCP scenario is given by Meinshausen, Smith, et al. (2011). Figure 2 shows that our fitted regional temperature anomalies in the North, the Tropics, the South, and the Ocean match well with the CMIP5 projections.[11]

10. For example, if we let $F_t = \eta$ (i.e., $M_t^{AT} = 2M_*^{AT}$ and $F_t^{EX} = 0$) starting from 2015, then our global mean temperature anomaly converges to 3.1°C after 5,500 years under the transition equations (3)–(6) with our calibrated parameter values.

11. However our climate system is still stylized. For example, it assumes a symmetric heat transport from the Tropics to the North or the South in the atmosphere and a symmetric heat

1.2. Economic System

Let $K_{t,i}$ be the regional capital state variables at time t and economic region $i = 1, 2$ (i.e., the North and the Tropics/South). Let $L_{t,i}$ be the exogenous regional population sizes. We follow DICE to let regional gross output be

$$Y_{t,i} \equiv A_{t,i} K_{t,i}^{\alpha} L_{t,i}^{1-\alpha}, \tag{7}$$

where $\alpha = 0.3$, $A_{t,i}$ is regional TFP that will be affected by climate change, and we let the mitigation expenditure function be

$$\Psi_{t,i} \equiv \theta_{1,t,i} \mu_{t,i}^{\theta_2} Y_{t,i},$$

where $\mu_{t,i}$ are emission control rates, $\theta_2 = 2.8$, and $\theta_{1,t,i}$ are the exogenous abatement costs in fractions of output in economic region i at time t.[12]

Global carbon emissions at time t are defined as

$$E_t \equiv \sum_{i=1}^{2} E_{t,i}^{\mathrm{Ind}} + E_t^{\mathrm{Land}},$$

where E_t^{Land} is exogenous global carbon emissions from biological processes, and $E_{t,i}^{\mathrm{Ind}} = \sigma_{t,i}(1 - \mu_{t,i}) Y_{t,i}$ are industrial emissions where $\sigma_{t,i}$ are the regional exogenous carbon intensities in region i.

The law of motion of the capital state variable $K_{t,i}$ is:

$$K_{t+1,i} = (1 - \delta_K) K_{t,i} + \hat{Y}_{t,i} - c_{t,i} L_{t,i}, \tag{8}$$

where $\delta_K = 0.1$ is the depreciation rate, $c_{t,i}$ is per capita consumption, and

---

transport between the atmosphere and the ocean. Moreover, the only ocean box assumes that changes in the oceanic temperature communicate immediately across the entire globe. Future work can extend our climate system to be more consistent with climate science. We thank a referee for stressing these points and for pushing us toward better modeling of the climate system as well as giving us useful references.

12. We follow DICE and Cai et al. (2019) to choose the parameter values for the mitigation cost function. However, the mitigation costs are uncertain. For example, Ueckerdt et al. (2019) show that different IAMs have different estimates of mitigation costs. Our mitigation cost function also allows very rapid reductions in emissions in ways that would not actually apply in the real world, as a stringent reduction of emissions requires a large renewable energy capital stock, and a transition to low-carbon technologies, etc. See, e.g., Acemoglu et al. (2016), Gillingham and Stock (2018), Jaakkola and van der Ploeg (2019), Baker et al. (2020), Baldwin et al. (2020), Cai (2021), and Campiglio et al. (2022).

$$\hat{Y}_{t,i} \equiv Y_{t,i} - \Psi_{t,i} = \left(1 - \theta_{1,t,i}\mu_{t,i}^{\theta_2}\right)Y_{t,i}$$

is net output.

1.3. Climate Impact to Economic Growth

Under the quadratic damage function of DICE for the Tropics/South, there is approximately 5% damage to output if the tropical regional surface temperature increase is the same as the global mean surface temperature in 2100 under the RCP8.5 scenario, that is, if the temperature increase in 2100 is 4.7°C. However, this damage calibration is at odds with the climate impact on regional economic growth estimated by Burke et al. (2015b) and Burke et al. (2018), who show a global nonlinear relationship between annual average temperature and growth rates in GDP per capita. Dell et al. (2012) show that there are large and negative effects of higher temperatures on growth rates of per capita output in poor countries. Dell et al. (2012) use a linear function of temperature for the impact on growth rates of per capita output. Here we change it to a quadratic function to reflect nonlinear effects as in Burke et al. (2015b) and Burke et al. (2018). Moyer et al. (2014) find that uncertainty in climate damage to economic growth creates a great range of estimates of the global SCC. Newell et al. (2021) show that model uncertainty on growth effects is much larger than level effects. Barnett et al. (2021) argue that misspecification and ambiguity concerns loom larger under larger model uncertainty. In their framework the larger model uncertainty surrounding growth effects should lead to more prudent behavior than even large model uncertainty surrounding level effects since growth effects compound over time. Here we deal with uncertainty in a rudimentary way by modeling growth effects or lagged level effects under different scenarios.

Burke et al. (2018) provide a baseline scenario of 165 countries' GDP paths, assuming temperature in year t changes the growth of GDP from year t to $t + 1$, under the RCP2.6 climate scenario and the population projection paths of the Shared Socioeconomic Pathway 1 (SSP1) (KC and Lutz 2017; Riahi et al. 2017), which represents a world shifting toward a sustainable path taking the green road with low resource and energy intensity. They also provide a baseline scenario of the countries' GDP paths assuming one-year or five-year lagged temperature effects on GDP growth. In a dynamic model with endogenous GDP, the growth rate of GDP from year t to $t + 1$ may be impacted by the growth rate of regional TFP from t to $t + 1$, or the no-lagged or lagged impact of the temperature anomaly on TFP levels, as the climate damage to TFP levels will reduce output, then impact investment in next-period capital, then impact future GDP too. We first aggregate Burke et al.'s (2018) projected GDP of 165 countries to our two regions for every year. In this study, we will choose three GDP scenarios from 2015 to 2099 in each economic region for our calibration: the baseline scenario with contemporaneous temperature effect on GDP growth (called "GDP scenario 1"), the baseline scenario with one-year lagged temperature effect on GDP growth (called "GDP scenario 2"), and the baseline scenario with five-year lagged temperature effect on GDP growth (called “GDP scenario 3”). We will also choose two TFP model assumptions: 10-year lagged climate impact on regional TFP levels (called “TFP model 1”), and climate impact on regional TFP growth (called “TFP model 2”).[13]

We first follow DICE and assume

$$A_{t+1,i}^{\mathrm{EX}} = \frac{A_{t,i}^{\mathrm{EX}}}{1 - g_{i,t}^{\mathrm{TFP,EX}}}$$

is the exogenous regional TFP under no climate change for economic region $i = 1, 2$ (i.e., the North and the Tropics/South), where

$$g_{i,t}^{\mathrm{TFP,EX}} = \zeta_{i,1}^{\mathrm{TFP}} \exp\left(-\zeta_{i,2}^{\mathrm{TFP}} t\right) \tag{9}$$

is the exogenous growth rate of regional TFP at time t under no climate impact. The initial TFP, $A_{0,i}^{\mathrm{EX}}$, is chosen such that $Y_{0,i} = A_{0,i}^{\mathrm{EX}} K_{0,i}^{\alpha} L_{0,i}^{1-\alpha}$ with the observed values of $Y_{0,i}$, $K_{0,i}$, and $L_{0,i}$ in the initial year 2015. Here $L_{t,i}$ are aggregated from Burke et al. (2018) under the SSP1 population scenario.[14] We estimate $\zeta_{i,1}^{\mathrm{TFP}}$ and $\zeta_{i,2}^{\mathrm{TFP}}$ using the aggregated regional GDP from the 165 projected countries' GDP of Burke et al. (2018) under no climate impact. In our structural estimation of the parameters, for each pair of $(\zeta_{i,1}^{\mathrm{TFP}}, \zeta_{i,2}^{\mathrm{TFP}})$, we solve the following simple optimal growth model

$$\begin{aligned} &\max_{c_{t,i}} \sum_{t=0}^{500} \beta^t u(c_{t,i}) L_{t,i}, \\ &\text{s.t. } K_{t+1,i} = (1 - \delta_K) K_{t,i} + (y_{t,i} - c_{t,i}) L_{t,i}, \end{aligned} \tag{10}$$

for each economic region i, where $y_{t,i} = A_{t,i}^{\mathrm{EX}} K_{t,i}^{\alpha} L_{t,i}^{-\alpha}$ is the per capita output affected by the parameters, β is the discount factor, and u is a per capita utility function from consumption:

$$u(c) = \frac{c^{1-\gamma}}{1-\gamma}, \tag{11}$$

where γ is elasticity of marginal utility. Here we follow DICE-2016R to choose $\gamma = 1.45$ and $\beta = 0.985$. We then use the solution of $y_{t,i}$ to match the growth rates of the

13. We tried the TFP model assumption with the climate impact on regional TFP without lagged effect and found that it cannot match well with any GDP data scenario, particularly for the Tropics/South. We also studied five-year lagged impact of temperature anomalies on regional TFP and found that they are relatively less well fitted than the 10-year lagged TFP model and that they do not have significant difference from the 10-year lagged impact. Thus we omit these analyses in this paper.

14. Burke et al. (2018) provide 165 countries' population paths only in this century. We extend them until 2515 for our model, assuming no change after 2099.

aggregated GDP of Burke et al. (2018) under no climate impact. That is, for each i, we find $(\zeta_{i,1}^{\mathrm{TFP}}, \zeta_{i,2}^{\mathrm{TFP}})$ by solving the following minimization problem:

$$\min_{\zeta_{i,1}^{\mathrm{TFP}}, \zeta_{i,2}^{\mathrm{TFP}}} \sum_{t=0}^{83} \left(\frac{y_{t+1,i}}{y_{t,i}} - \frac{y_{t+1,i}^{\mathrm{BDD,NoCC}}}{y_{t,i}^{\mathrm{BDD,NoCC}}} \right)^2 \tag{12}$$

where $y_{i,t}$ and $y_{t,i}^{\mathrm{BDD,NoCC}}$ are, respectively, model (10)'s solution and the per capita GDP of Burke et al. (2018) under no climate impact from 2015 to 2099. After we obtain the estimated values of $\zeta_{i,1}^{\mathrm{TFP}}$ and $\zeta_{i,2}^{\mathrm{TFP}}$ and their associated $g_{i,t}^{\mathrm{TFP,EX}}$ and $A_{t,i}^{\mathrm{EX}}$, we will use the GDP scenarios to estimate climate impact on TFP.

In our baseline case (i.e., case 1), we use GDP scenario 1 to calibrate TFP model 1, which assumes that climate change has a 10-year lagged effect on regional TFP levels. That is,

$$A_{t,i} = \frac{A_{t,i}^{\mathrm{EX}}}{1 + \sum_{s=t-10}^{t} \left(\delta_i^{\mathrm{TFP}}\right)^{t-s} \left(\zeta_{i,3}^{\mathrm{TFP}} \left(T_{s,i}^{\mathrm{AT}} - T_{0,i}^{\mathrm{AT}} \right) + \zeta_{i,4}^{\mathrm{TFP}} \left(T_{s,i}^{\mathrm{AT}} - T_{0,i}^{\mathrm{AT}} \right)^2 \right)}, \tag{13}$$

where $T_{0,i}^{\mathrm{AT}}$ is the temperature anomaly in our initial year (i.e., 2015), and the regional TFP in year t depends on the atmospheric temperature anomaly, $T_{t,i}^{\mathrm{AT}}$, of year t and of the last 10 years. The initial TFP $A_{0,i}$ is set to be $A_{0,i}^{\mathrm{EX}}$. Here the regional atmospheric temperature anomalies $T_{s,i}^{\mathrm{AT}}$ are the ensemble mean of the CMIP5 models' annual projections under the RCP2.6 scenario used in Burke et al. (2018) for GDP scenario 1. We use GDP scenario 1 to calibrate parameters $(\zeta_{i,3}^{\mathrm{TFP}}, \zeta_{i,4}^{\mathrm{TFP}}, \delta_i^{\mathrm{TFP}})$, where $\zeta_{i,3}^{\mathrm{TFP}}$ and $\zeta_{i,4}^{\mathrm{TFP}}$ represent the nonlinear climate impact of temperature increase on TFP levels, and δ_i^{TFP} represents the persistence factor of their impact in each economic region i. We apply a similar structural estimation method in finding $(\zeta_{i,1}^{\mathrm{TFP}}, \zeta_{i,2}^{\mathrm{TFP}})$ to estimate $(\zeta_{i,3}^{\mathrm{TFP}}, \zeta_{i,4}^{\mathrm{TFP}}, \delta_i^{\mathrm{TFP}})$ under climate impact. That is, we let $y_{t,i} = A_{t,i} K_{t,i}^{\alpha} L_{t,i}^{-\alpha}$ using the TFP equation (13) with the prespecified $A_{t,i}^{\mathrm{EX}}$, and solve (10) repeatedly with different values of $(\zeta_{i,3}^{\mathrm{TFP}}, \zeta_{i,4}^{\mathrm{TFP}}, \delta_i^{\mathrm{TFP}})$ until the distance between the growth rates of per capita GDP from (10) and the ones from GDP scenario 1 is minimal.

In our case 2, we use GDP scenario 1 to calibrate TFP model 2, which assumes that the growth of regional TFP from year t to $t + 1$ depends on year t's atmospheric temperature anomaly, implying a persistent impact on TFP levels. That is, we specify the paths of regional TFP at economic region i to be

$$A_{t+1,i} = \frac{A_{t,i}}{1 - g_{i,t}^{\mathrm{TFP,EX}} \exp\left(-\left(\zeta_{i,3}^{\mathrm{TFP}} \left(T_{t,i}^{\mathrm{AT}} - T_{0,i}^{\mathrm{AT}} \right) + \zeta_{i,4}^{\mathrm{TFP}} \left(T_{t,i}^{\mathrm{AT}} - T_{0,i}^{\mathrm{AT}} \right)^2 \right) \right)}. \tag{14}$$

With this TFP model assumption, we estimate $(\zeta_{i,3}^{\mathrm{TFP}}, \zeta_{i,4}^{\mathrm{TFP}})$ to minimize the distance of growth rates of per capita output between GDP scenario 1 and our model (10)'s solution with $y_{t,i} = A_{t,i} K_{t,i}^{\alpha} L_{t,i}^{-\alpha}$ using the TFP equation (14) and the prespecified $g_{i,t}^{\mathrm{TFP,EX}}$.

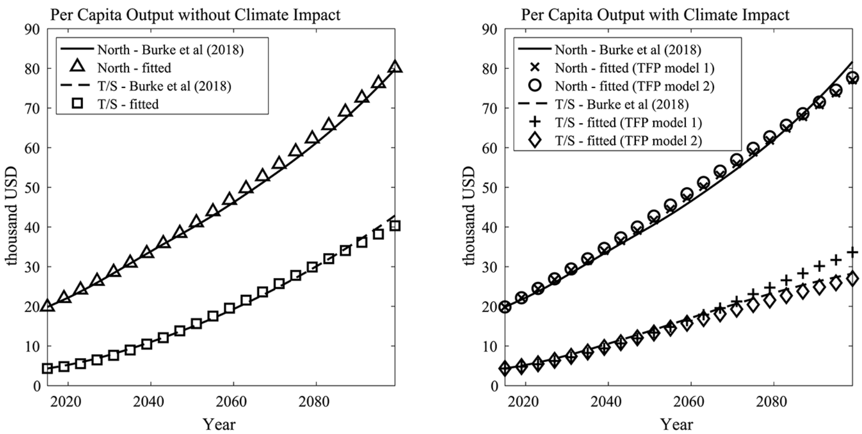

Figure 3. Fitting regional GDP with/without climate impact on economic growth in the baseline case (i.e., total factor productivity [TFP] model 1 [13] calibrated with GDP scenario 1). *Left panel*, regional per capita output without climate impact on economic growth. *Right panel*, regional per capita output with climate impact on economic growth. *Solid lines*, per capita output of the North from Burke et al. (2018) with/without climate impact; *triangles*, fitted per capita output of the North without climate impact; *dashed lines*, per capita output of the Tropics/South (i.e., T/S in the legend) from Burke et al. (2018) with/without climate impact; *squares*, fitted per capita output of the Tropics/South without climate impact; *marks*, fitted per capita output of the North using TFP model 1 for climate impact; *circles*, fitted per capita output of the North using TFP model 2 for climate impact; *pluses*, fitted per capita output of the Tropics/South using TFP model 1 for climate impact; *diamonds*, fitted per capita output of the Tropics/South using TFP model 2 for climate impact.

Figure 3 shows that our calibrated regional per capita outputs match well with GDP scenario 1.[15] Moreover, we see that climate change has little impact in the North under the RCP2.6 climate scenario, which keeps the global average temperature anomaly under around 1.5°C. In contrast, climate change significantly decreases per capita output in the Tropics/South in 2099 from $42,905 to only $28,269, that is, 66% of its regional per capita output in a world without climate damage, under GDP scenario 1. We caution that there is a substantial amount of uncertainty present in this kind of extrapolation. For example, figure 3 may not account for all the uncertainties in adaptive responses in the Tropics/South to climate change; for example, the Tropics/South may

15. The per capita outputs of Burke et al. (2018) in fig. 3 are adjusted to start with our initial per capita output from the World Bank data of output in 2015, which are used to compute our initial TFP, but the growth rates are not adjusted. Note that we use the growth rates of Burke et al. (2018) for our calibration, so the calibrated parameter values of $\zeta_{i,1}^{\mathrm{TFP}}, \ldots, \zeta_{i,4}^{\mathrm{TFP}}$ and δ_i^{TFP} are not affected by the adjustment.

have a large increase of air conditioning, which may have a large impact on economic production (Barreca et al. 2016).

In our cases 3–4 and 5–6, we use GDP scenarios 2 and 3, respectively, to calibrate the two TFP models. Figure 4 shows that either of our TFP models can lead to a good match with either of GDP scenarios 2–3. Cases 3–4 associated with GDP scenario 2 (the left panel of fig. 4) exhibit a pattern similar to the baseline case: climate change has little impact in the North (but its damage is slightly larger than in cases 1–2 associated with GDP scenario 1) and substantial damage in the Tropics/South, but the damage is relatively less: climate change reduces the Tropics/South's per capita output in 2099 to $33,567, that is, 78% of its per capita output in a world without climate damage under GDP scenario 2. However, in cases 5–6 associated with GDP scenario 3 (the right panel of fig. 4), climate change significantly reduces output in both economic regions: in 2099 the North has only $61,074 (i.e., 77% of its regional per capita output in a world without climate damage) and the Tropics/South has only $30,865 (but is still higher than GDP scenario 1). From the six cases, we see that the climate change impact in the North is highly uncertain, while climate change always causes severe damages in the Tropics/South.

2. COOPERATION AND NONCOOPERATION

We solve two dynamic models, one for a cooperative world, another for a noncooperative world.

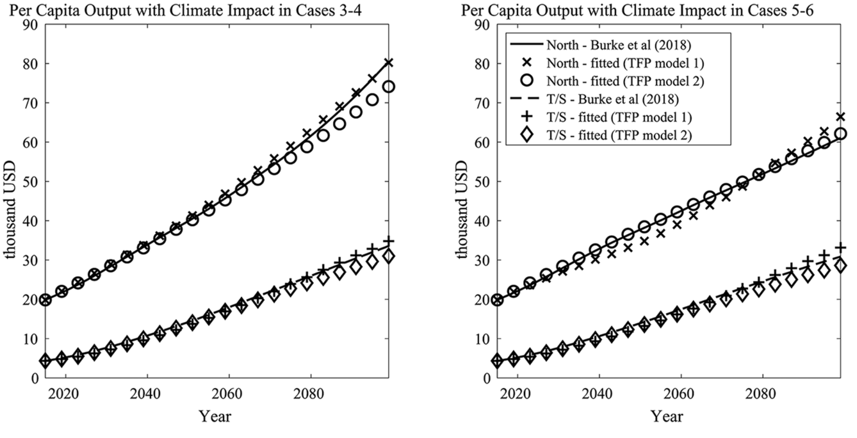

Figure 4. Fitting regional GDP with climate impact on economic growth under cases 3–4 and 5–6. *Left panel*, cases 3–4 (i.e., the total factor productivity [TFP] models calibrated with GDP scenario 2). *Right panel*, cases 5–6 (i.e., the TFP models calibrated with GDP scenario 3). T/S = Tropics/South.

2.1. Cooperative World

In our model under cooperation, a social planner maximizes the present value of the sum of regional utility across economic regions and time with annual time steps by choosing paths of per capita consumption and emission control rates. Our regional utility is equal to the product of regional population and per capita utility, so the social welfare in each economic region i is

$$\sum_{t=0}^{\infty} \beta^t u(c_{t,i}) L_{t,i}.$$

The social planner solves the following dynamic optimization problem:

$$\max_{c_{t,i}, \mu_{t,i}} \sum_{t=0}^{\infty} \beta^t \sum_{i=1}^{2} u(c_{t,i}) L_{t,i}, \tag{15}$$

with four control variables $(c_{t,1}, c_{t,2}, \mu_{t,1}, \mu_{t,2})$ at each time t. The optimization is subject to the transition laws of three carbon concentration levels, four temperature levels, and two regional capital state variables. Since the choice of discount factor $\beta = 0.985$ makes the welfare after 500 years have little impact on the first 100 years' solutions, we follow DICE-2016R to approximate the infinite-horizon problem (15) by a finite-horizon problem with 500 years.

2.2. Noncooperative World

In our model under noncooperation, each economic region's decision maker maximizes the present value of the sum of their own regional utility across time by choosing their own paths of per capita consumption and emission control rates. That is, we simultaneously solve the following system of two dynamic optimization problems:

$$\max_{c_{t,i}, \mu_{t,i}} \sum_{t=0}^{\infty} \beta^t u(c_{t,i}) L_{t,i}, \ i = 1, 2, \tag{16}$$

while each economic region's optimization is subject to the transition laws of three carbon concentration levels, four temperature levels, and their own regional capital, assuming that the other economic region's emission path is given. This is a dynamic game problem. We solve its open-loop Nash equilibrium (OLNE), that is, the optimal solution depends on only the initial condition and time. The concept of the OLNE could be interpreted as a situation in which individual agents, regions in our case, enter an agreement to commit to a future path of carbon emission at the beginning of the agreement. This type of equilibrium concept might not be as satisfactory—in terms of strong time consistency—as the feedback Nash equilibrium concept, but it has the computational advantages of solving open-loop versus feedback,[16] while the OLNE solution may be fairly close to the feedback Nash equilibrium. We use an iterative method to solve the OLNE; see appendix A2.

2.3. Regional Social Cost of Carbon and Carbon Tax

In Nordhaus (2017), the regional SCC is defined as the present value of future damages in a region caused by one extra ton of global carbon emissions in the current period. Ricke et al. (2018) use the same concept in computing the country-level SCC (i.e., country-level contributions to the global SCC). But with their concept, we cannot derive that the optimal regional carbon tax is equal to the regional SCC, as the global SCC is the sum of their regional SCCs over all regions but the global carbon tax cannot be the sum of regional carbon taxes.

In this study, we follow van der Ploeg and de Zeeuw (2016) and Cai et al. (2019) to use a different concept of the regional SCC, such that the regional SCC is equal to the regional carbon tax when the emission control rate does not hit its lower or upper bound (Cai et al. 2017; Cai and Lontzek 2019), where the regional carbon tax is defined as $-1{,}000\ \theta_{1,t,i}\theta_2\mu_{t,i}^{\theta_2-1}/\sigma_{t,i}$, following DICE, Cai et al. (2017) and Cai and Lontzek (2019). Thus, the regional SCC can be negative if the emission control rate hits its lower bound 0 or can be much larger than the regional carbon tax if the emission control rate hits its upper bound.

We define the regional cooperative SCC in economic region i as

$$\tau_{t,i}^{\mathrm{SP}} = -1{,}000\left(\frac{\partial V_t^{\mathrm{SP}}}{\partial M_t^{\mathrm{AT}}}\right)/\left(\frac{\partial V_t^{\mathrm{SP}}}{\partial K_{t,i}}\right),$$

where $V_t^{\mathrm{SP}} = \max_{c_{s,i},\mu_{s,i}}\sum_{s=t}^{\infty}\beta^t\sum_{i=1}^{2}u(c_{s,i})L_{s,i}$ is the global welfare starting from year t with a given starting state vector $(K_{t,1},\ K_{t,2},\ M_t^{\mathrm{AT}},\ \ldots)$. In its computation for our deterministic model, it is equivalent to replacing the numerator by the shadow price of the transition equation of atmospheric carbon concentration at year t, and the denominator by the shadow price of the regional capital transition equation.

We define the regional noncooperative SCC as

$$\tau_{t,i}^{\mathrm{OLNE}} = -1{,}000\left(\frac{\partial V_{t,i}^{\mathrm{OLNE}}}{\partial M_t^{\mathrm{AT}}}\right)/\left(\frac{\partial V_{t,i}^{\mathrm{OLNE}}}{\partial K_{t,i}}\right),$$

16. Solving feedback Nash equilibrium requires extensive supercomputer computing resources, which are unavailable to us, as our model has 500 periods and 29 endogenous state variables (three for carbon concentration levels, four for contemporaneous temperature levels in the regional atmosphere and ocean, two for regional capitals, and 20 for the 10 years' lagged atmospheric temperature anomalies in both economic regions), and value functions have kinks due to the occasionally binding constraint on the upper bound of emission control rates.

where $V_{t,i}^{\mathrm{OLNE}} = \max_{c_{s,i},\mu_{s,i}} \Sigma_{s=t}^{\infty} \beta^t u(c_{s,i}) L_{s,i}$ is the optimal regional welfare starting from year t with a given starting state vector $(K_{t,1}, K_{t,2}, M_t^{\mathrm{AT}}, \ldots)$ under OLNE. In its computation, it is equivalent to replacing the numerator by the shadow price of the transition equation of atmospheric carbon concentration at year t, and the denominator by the shadow price of the regional capital transition equation, for each economic region $i = 1, 2$.

3. RESULTS

We first report the results in the baseline case. Figure 5 shows the paths of the regional SCC (the left panel) and optimal regional carbon taxes (the right panel) in the economic regions in a cooperative or noncooperative world. The initial cooperative SCC for the North is very high (\$806/tCO_2), 6.9 times the initial cooperative SCC for the Tropics/South (\$117/tCO_2), although the North experiences little impact on its economic growth from climate change in this century according to GDP scenario 1 as shown in figure 3. It is not surprising that the North has such a large SCC under cooperation, because consumption in the poor countries in the Tropics/South has higher marginal utility than in the rich countries in the North, and then the social planner uses differentiated carbon taxes to achieve some second-best redistribution, under our assumption that there are no direct transfers of physical consumption or investment goods between the regions.[17]

Moreover, the cooperative SCC for the North is much larger than the cooperative optimal regional carbon tax for the North, because the emission control rate for the North has hit the upper bound, 1, starting from the initial period.[18] That is, under cooperation the North would have zero emissions starting from the first period, while the Tropics/South would have zero emissions starting from 2050. The large cooperative SCC and carbon taxes of the North cannot be regarded as a realistic policy proposal since there are very few unselfish and completely cooperative sovereigns in the real world. Moreover, our model, like DICE, has no adjustment costs for changes in emissions control, so it is not realistic to have the emission control rate hit the upper bound in only one period. However, this polar cooperative world provides insight into

17. If we allow direct transfers of consumption and capital investment without any border friction costs under cooperation, then the regional SCC is the same across the regions. For example, the initial SCC becomes \$259 for both economic regions, much lower than the average of \$806 and \$117 or their population weighted average (\$381), due to the lower marginal utility in the richer Tropics/South under the free allocation of consumption and capital investment.

18. We follow DICE-2016 (Nordhaus 2017) and assume that emissions must be nonnegative until 150 years later (that is, the emission control rates $\mu_{t,i} \leq 1$ if $t \leq 150$, and $\mu_{t,i} \leq 1.2$ otherwise). If we allow earlier negative emissions, then the cooperative SCCs will be smaller, because future temperature will be lower and then climate damages will be smaller. For example, if we allow negative emissions starting from the first period, then the initial cooperative SCC is reduced to \$486 for the North or \$81 for the Tropics/South.

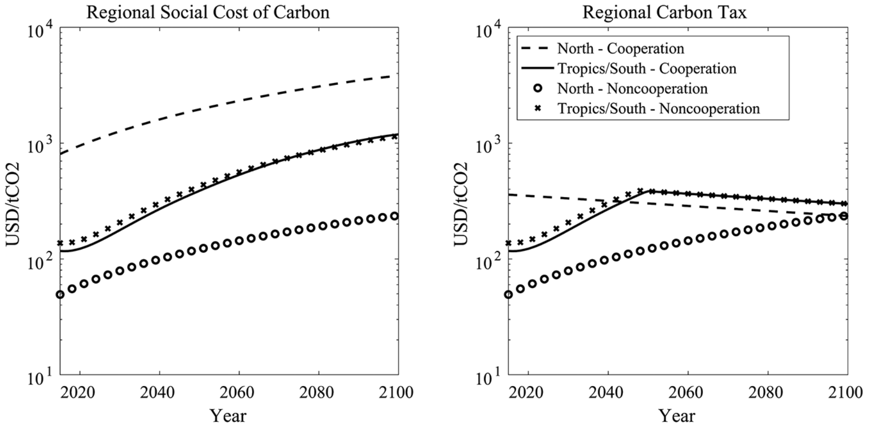

Figure 5. Regional SCC and optimal regional carbon taxes under climate damage in the baseline case. *Left panel*, regional SCC. *Right panel*, optimal carbon tax. *Dashed lines*, solution for the North under cooperation; *solid lines*, solution for the Tropics/South under cooperation; *circles*, solution for the North under noncooperation; *marks*, solution for the Tropics/South under noncooperation.

the structure of optimal carbon taxes. This structure suggests that when the rich countries in the North are cooperative, it is optimal for them to reduce emissions in a much more stringent way than the poor countries in the Tropics/South in order to help maximize global welfare. Otherwise the Tropics/South would have much higher damages from climate change so global welfare would be reduced significantly. This behavior leads to the very high cooperative SCC and carbon taxes in the North.

The noncooperative SCC for the North is dramatically reduced to $49 in the first period and then gradually increases. Moreover, figure 5 shows that the whole path of the SCC and carbon taxes for the North in the noncooperative world is dramatically lower than in the cooperative world. But note that the values of the SCC are, relatively, not small in comparison to the existing literature. For example, in DICE-2016R the global SCC in 2015 is only $31, much smaller than our regional SCC even under noncooperation. This is because the quadratic damage function in DICE-2016R has much smaller damages than ours under the same temperature. For example, if the global and regional temperature increase over the initial year is 1°C, then in DICE-2016R the global temperature anomaly is 1.85°C and reduces contemporaneous output by 0.8% (the temperature anomaly has no lagged effect in future output), but our TFP model 1 estimates a 1.2% reduction of contemporaneous output in the North and a 12.1% reduction in the Tropics/South, and the temperature anomaly has a lagged effect on the next 10 years' output.

Moreover, the nonlinearity in our TFP models is much larger. For example, if the temperature increase over the initial year is 2°C, then the damage estimate in DICE-2016R is 1.9% of contemporaneous output, but ours is 3.2% in the North and 39.1% in the Tropics/South while there are still lagged effects in future output. For the Tropics/South, its initial noncooperative SCC or carbon tax increases to $137, 17% higher than in the cooperative world.[19] This finding is different from those in the literature which show that noncooperation will always lead to smaller carbon taxes than under cooperation. The intuition behind this finding is that smaller carbon taxes in the North under noncooperation lead to much higher emissions and then much higher temperatures in the Tropics/South (see fig. 7), so that the Tropics/South has higher marginal damages and a higher SCC. Therefore, even under noncooperation, both economic regions should adopt stringent climate policy.[20]

The main driver of these high regional SCCs and carbon taxes is that we assume the serious climate damage to economic growth in the Tropics/South. Figure 6 shows that in our model with optimal climate policy, the per capita output of the Tropics/South in 2100 is $34,927 in the cooperative world or $28,021 in the noncooperative world, while the per capita output of the North in 2100 is $77,484 under cooperation or $75,091 under noncooperation. That is, relative to cooperation, noncooperation reduces output by an extra 3.1% (i.e., $2,393 per capita) in the North but reduces output by a substantial extra 20% (i.e., $6,907 per capita) in the Tropics/South in 2100.

Figure 7 displays paths of regional atmospheric temperature anomalies. Under cooperation, with the most stringent climate policy shown in figure 5, the atmospheric temperature anomaly is 2.1°C in the North, 1.3°C in the Tropics, and 1.1°C in the South, and the global average is below 1.5°C. But with the noncooperative but still stringent climate policy, in 2100 the atmospheric temperature anomaly is 2.7°C in the North, 1.8°C in the Tropics, and 1.4°C in the South, and the global average is below 2.0°C. Thus, the temperature anomalies are compatible with the SSP1 population scenario that is used in our calibration.

We run cases 2–5 to test the sensitivity of our results to different damage specifications. Figure 8 displays the regional SCC under cooperation or noncooperation, where we use "baseline damages" for cases 1–2 associated with the baseline GDP scenario 1, "low damages in Tropics/South" for cases 3–4 associated with GDP scenario 2, and "high damages in North" for cases 5–6 associated with GDP scenario 3, to

19. Since the emission control rates do not hit their upper bound before 2048 in the Tropics/South under cooperation or noncooperation, the regional optimal carbon tax path is identical to the regional noncooperative SCC path for the Tropics/South before 2048 as shown in fig. 5. For the same reason, the North has identical paths between the SCC and carbon tax under noncooperation in the whole century.

20. If we allow negative emissions starting from the first period, the initial noncooperative SCC is $47 for the North or $134 for the Tropics/South. That is, the relaxation of negative emissions has little impact on the initial noncooperative SCC in this baseline case, as the emissions under the noncooperative solution are strictly positive before 2048.

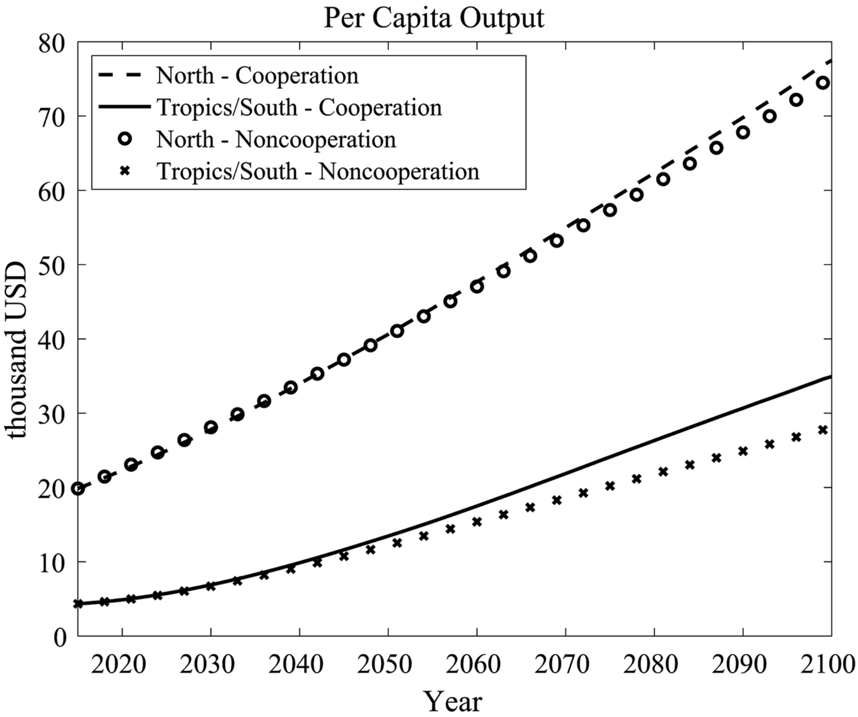

Figure 6. Regional per capita output under cooperation and noncooperation in the baseline case.

highlight the properties of the GDP scenarios as shown in figures 3–4. Figure 8 shows a pattern similar to the left panel of figure 5: the North in the cooperative world (the top left panel) has the largest SCC for each case, in comparison to the North under noncooperation (the bottom left panel) or the Tropics/South (the right panels). In the North (the left panels), the "high damages in North" cases 5–6 have a larger SCC than the other cases when comparing the three lines associated with 10-year lagged climate impact (i.e., cases 1, 3, and 5), or comparing the three lines associated with persistent climate impact (i.e., cases 2, 4, and 6), because the North has the larger loss in GDP scenario 3 with "high damages in North" (associated with cases 5–6). Similarly, in the Tropics/South (the right panels), the "high damages in North" cases 5–6 have a larger SCC under cooperation but not under noncooperation, because both economic regions have large climate damage in GDP scenario 3 with "high damages in North" but the Tropics/South has smaller damage than in GDP scenario 1 with the baseline damages (associated with cases 1–2). Since the climate damages to the North in cases 1–2 are the smallest among all cases, in the noncooperative world

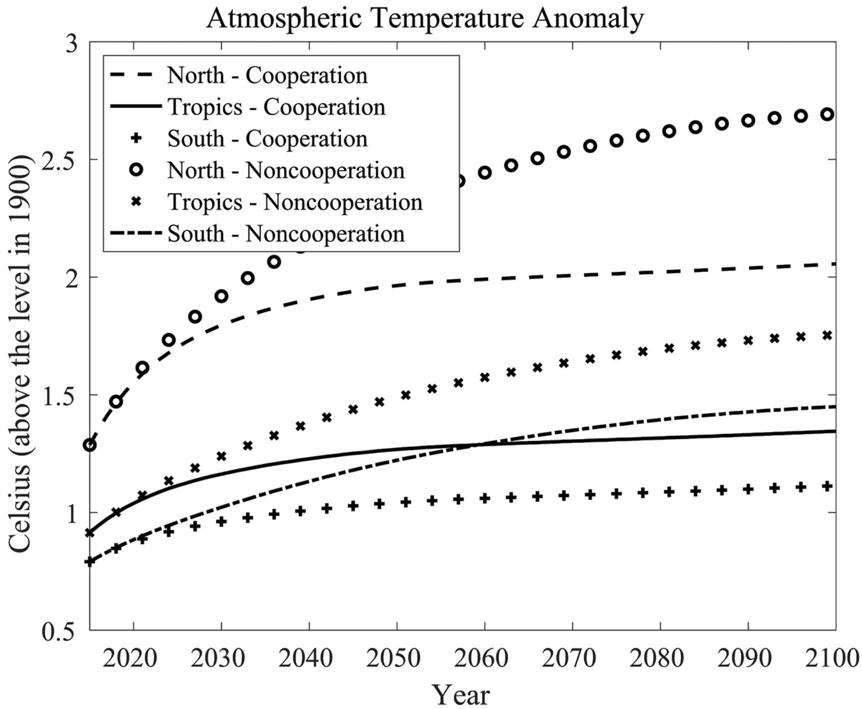

Figure 7. Atmospheric temperature anomaly under climate damage in the baseline case

cases 1–2 have the smallest SCC in the North (the bottom left panel). However, in the cooperative world, the "low damages in Tropics/South" cases 3–4 (associated with GDP scenario 2) have a much lower SCC than in the "baseline damages" cases 1–2, respectively, in the North (the top left panel), because the marginal utility of the Tropics/South is higher due to the lower damages in the Tropics/South in GDP scenario 2.

Figure 8 shows that the climate effect on TFP growth (case 2, 4, or 6) leads to a larger SCC in the initial periods than the 10-year lagged effect on TFP levels (case 1, 3, or 5). This occurs because the climate effect on TFP growth is persistent on TFP levels, so both economic regions want to impose more stringent climate policy and control the temperature anomaly at earlier periods so that they suffer less damage in later periods. We also see that the climate effect on TFP growth (associated with cases 2, 4, and 6) leads to a smaller growth of the SCC in later periods or even negative growth in some cases (e.g., starting from 2060 the SCC in the Tropics/South under noncooperation starts to decrease and continues to decrease as we move toward the end of this century in case 2). This occurs because the exogenous TFP growth rate under no climate impact (i.e., $g_{i,t}^{\mathrm{TFP,EX}}$ in eq. [9]) follows DICE to have a declining path over time and converges to zero as time $t \rightarrow \infty$, which implies that the climate effect on TFP levels

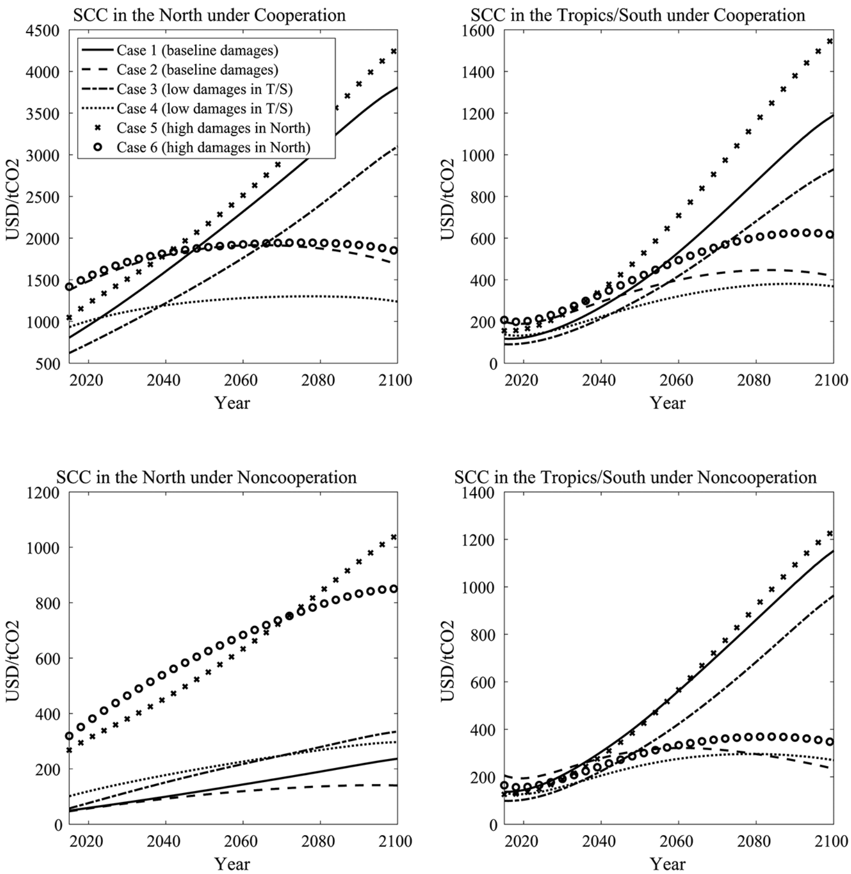

Figure 8. Regional SCC in the six cases under cooperation or noncooperation. *Solid lines*, case 1 with the baseline damages and 10-year lagged climate impact; *dashed lines*, case 2 with the baseline damages and persistent climate impact; *dash-dotted lines*, case 3 with "low damages in Tropics/South" and 10-year lagged climate impact; *dotted lines*, case 4 with "low damages in Tropics/South" and persistent climate impact; *marks*, case 5 with "high damages in North" and 10-year lagged climate impact; *circles*, case 6 with "high damages in North" and persistent climate impact.

also converges to zero, while TFP model 1 does not have this issue as it assumes a direct climate effect on TFP levels. If we cut the value of the declining rate of the exogenous TFP growth rates (i.e., $\zeta_{i,2}^{\mathrm{TFP}}$) in half, then we find that the growth rate of the SCC in each of the cases with persistent climate impact (i.e., cases 2, 4, 6) becomes larger and is not declining toward the end of this century (see fig. A2 in app. A4), because a smaller $\zeta_{i,2}^{\mathrm{TFP}}$ implies a larger $g_{i,t}^{\mathrm{TFP,EX}}$, then a larger climate impact on TFP levels according to equation (14).

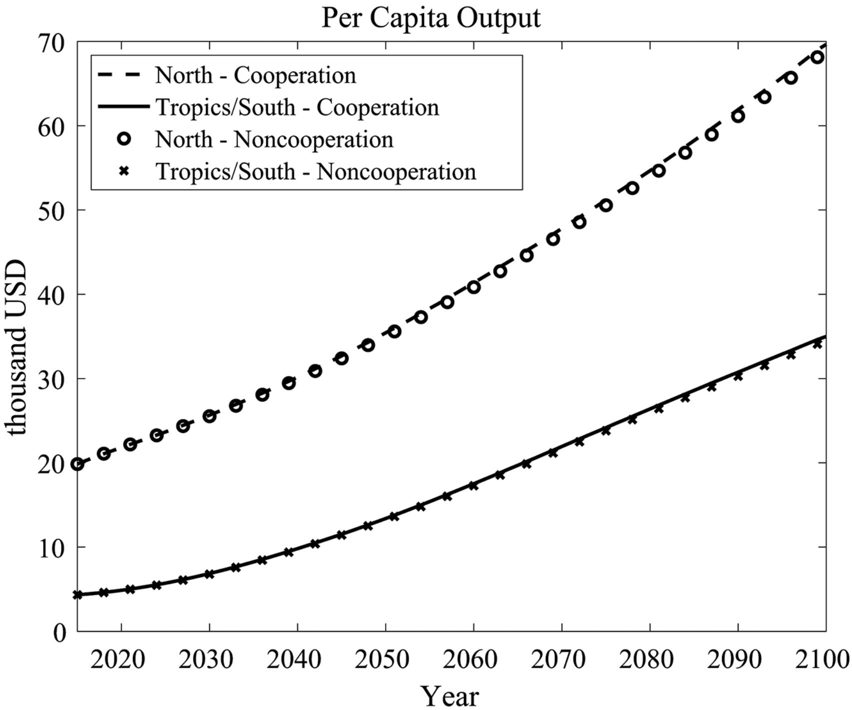

Figure 9. Regional per capita GDP in case 5 with 10-year lagged climate impact and "high damages in North" under cooperation and noncooperation.

Figure 9 displays the per capita output in case 5 with 10-year lagged climate impact and "high damages in North."[21] Figure 9 shows that noncooperation causes only a little extra loss in each economic region, in comparison to the cooperative solution. While it looks a bit strange, this occurs because under either cooperation or noncooperation, both economic regions hit the upper bound of the emission control rates soon with small time differences between cooperative and noncooperative solutions. For example, the Tropics/South hits the upper bound in 2044 and 2049 under cooperation and noncooperation, respectively. Thus, although the SCC is high (and higher than cases 1 and 3 from fig. 8), it cannot affect the temperature; only the emission control rates can. That is, there is little difference in emissions between cooperation and noncooperation, so there is little difference in the temperature anomaly, then little difference in climate damage, and finally little difference in output: noncooperation reduces output by an

21. We omit the other cases because the figures for cases 2–4 are similar to fig. 6 and the figure for case 6 is similar to fig. 9.

extra 1.2% (i.e., $870 per capita) in the North, and by an extra 1.6% (i.e., $548 per capita) in the Tropics/South in 2100, in comparison to the cooperative solution. Note that the small difference between cooperative and noncooperative solutions happens because the huge climate damage in both economic regions forces them to adopt extremely stringent climate policy to control carbon emissions even without cooperation. That is, no matter whether they choose cooperation or noncooperation, both economic regions should choose very stringent climate policy.

Table 1 lists the initial SCC and per capita output in 2100 for all six cases. We see that in comparison to the 10-year lagged effect on TFP levels (case 1, 3, or 5), the climate effect on the TFP growth (case 2, 4, or 6) leads to a much larger SCC in 2015 in both economic regions under cooperation, and in the Tropics/South under noncooperation, although both TFP models are calibrated with the same GDP scenarios. This happens because the impact on TFP growth is permanent on all future TFP, but the impact on TFP levels is not, although both influence GDP growth. Moreover, the smallest SCC in the initial period, \$47/tCO_2, in the North under noncooperation in case 2, is still not small in comparison to the existing literature (e.g., in DICE 2016R the global SCC in 2015 is only $31), while the highest initial SCC is up to $319 in the North under noncooperation in case 6 (persistent climate impact with "high damages in North"), $206 in the Tropics/South under noncooperation in case 2 (persistent climate impact with the baseline damages), $1,417 in the North under cooperation in case 6, or $207 in the Tropics/South under cooperation in case 6.

Table 1 also shows that noncooperation causes an extra reduction in output for both economic regions for all cases in comparison to the cooperative solution, while

Table 1. SCC in 2015 and Per Capita Output in 2100

	SCC in 2015 (\$/tCO_2)				Per Capita Output in 2100			
	Cooperation		Noncooperation		Cooperation		Noncooperation	
Case	North	T/S	North	T/S	North	T/S	North	T/S
1	806	117	49	137	77,484	34,927	75,091	28,021
2	1,376	199	47	206	78,267	30,104	76,004	23,285
3	622	91	57	99	80,660	35,432	78,397	32,077
4	933	138	101	132	75,091	32,779	72,089	29,490
5	1,048	156	268	126	69,653	34,993	68,782	34,445
6	1,417	207	319	164	66,825	31,573	65,259	30,871

Note. Case 1: 10-year lagged climate impact with the baseline damages; case 2: persistent climate impact with the baseline damages; case 3: 10-year lagged climate impact with "low damages in Tropics/South"; case 4: persistent climate impact with "low damages in Tropics/South"; case 5: 10-year lagged climate impact with "high damages in North"; case 6: persistent climate impact with "high damages in North." T/S = Tropics/South.

loss in the Tropics/South is large in cases 1–4. Moreover, table 1 shows that there is no significant difference in the Tropics/South's SCC between cooperation and noncooperation, while the difference is significant in the North, as the Tropics/South will suffer a large loss from climate change while the North will not. But here we also ignore the spillover effects of international trade, migration, and social conflict between regions in our model, so the North might suffer a larger loss in output, particularly under noncooperation (see, e.g., Burke et al. 2015a; Carleton and Hsiang 2016; Mach et al. 2019; Kortum and Weisbach 2021).

In addition to the above analysis with different TFP models calibrated from different climate damage estimates (i.e., GDP scenarios), we also do sensitivity analysis over 0.25, 0.5, or 0.75 times the calibrated values of both $\zeta_{i,1}^{\text{TFP}}$ and $\zeta_{i,2}^{\text{TFP}}$ in the baseline case for both $i = 1, 2$. Figure 10 shows that the initial regional SCCs are almost linear in the levels of impact in each economic region under cooperation or noncooperation. For instance, if we reduce the impact parameters, $\zeta_{i,1}^{\text{TFP}}$ and $\zeta_{i,2}^{\text{TFP}}$, to half their values in the economic regions, then the initial regional SCCs are also nearly half: \$424 for the North and \$62 for the Tropics/South under cooperation, or \$26 for the North and

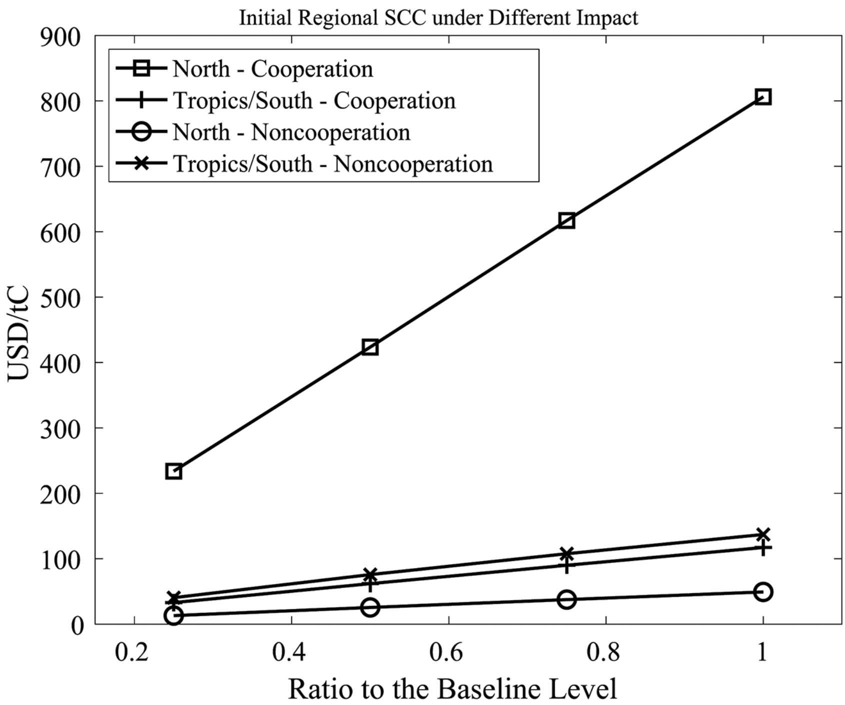

Figure 10. Initial regional SCC under different levels of impact

$76 for the Tropics/South under noncooperation. Moreover, this almost linear relation also holds in later years until 2050.

4. DISCUSSION AND CONCLUSION

The regional SCC and the impact of climate change on GDP are well-researched issues in the economics of climate change. The present study, using a three-region model, provides new insights on the regional SCC under cooperation or noncooperation when climate change impacts economic growth. First, we find that whether there is cooperation or noncooperation, it is always optimal for economic regions to choose stringent climate policies and keep the global mean temperature anomaly in this century below 1.5°C under cooperation or 2°C under noncooperation. Second, we show the difference in the regional SCC associated with a cooperative or noncooperative world. Our results suggest that a shift toward cooperation in international climate change policy will result in substantially higher regional SCCs for the developed North relative to the developing Tropics/South, and substantively higher GDP per capita for the Tropics/South, with a small increase in GDP per capita for the North. Third, if climate change affects TFP growth instead of TFP levels, then our results, which are in line with recent literature, indicate that damages and therefore regional SCCs are much higher except for the noncooperative SCC in the North.

In the existing climate change literature, there is considerable uncertainty surrounding the specification and the parameterization of the damage function in IAMs. There is also strong criticism of the traditional damage functions which are associated with level—not growth—effects of climate change. Our results suggest that, in order to achieve efficient climate policy, the issue of whether climate change affects levels or growth, or both, needs to be carefully addressed. We believe that our analysis of cooperative or noncooperative behavior at the regional level, which accounts for growth effects, introduces a novel aspect in the design of climate policy.

The results obtained in this study extend the current literature and suggest promising areas of future research. For example, incorporating the spillover effects of international trade, migration, and social conflict between regions into our model might have a significant impact on the optimal climate policy, particularly in the North. Moreover, a finer spatial resolution or more realistic economic regions could also play an important role in policy design.

APPENDIX

A1. The Carbon Cycle and Its Calibration

The carbon cycle dynamics is

$$\mathbf{M}_{t+1} = \mathbf{\Phi}_{\mathrm{M}}\mathbf{M}_t + (E_t, 0, 0)^\top, \tag{A1}$$

where the transition matrix of the carbon cycle is

$$\Phi_M = \begin{bmatrix} 1-\phi_{12} & \phi_{12}M_*^{AT}/M_*^{UO} & \\ \phi_{12} & 1-\phi_{12}M_*^{AT}/M_*^{UO}-\phi_{23} & \phi_{23}M_*^{UO}/M_*^{DO} \\ & \phi_{23} & 1-\phi_{23}M_*^{UO}/M_*^{DO} \end{bmatrix}, \quad \text{(A2)}$$

where M_*^{AT}, M_*^{UO}, M_*^{DO} are preindustrial carbon concentrations in the atmosphere, the upper ocean and the deep ocean, respectively. MAGICC 6 (Meinshausen, Raper, et al. 2011) provides four global RCP scenarios, that is, RCP2.6, RCP4.5, RCP6, and RCP8.5, which include both emission paths and carbon concentration in the atmosphere. The parameters ϕ_{12} and ϕ_{23} are calibrated against the four RCP scenarios. That is, we solve the following minimization problem:

$$\min_{\phi_{12},\phi_{23}} \sum_{j=1}^{4}\sum_{t=0}^{85}\left|M_t^{AT,j}/M_t^{MAGICC,AT,j}-1\right|,$$

subject to the carbon cycle system (A1) for each RCP scenario $j = 1, \ldots, 4$ (represented in the superscript) over the 85-year time horizon (from the initial year 2015 to 2100). Here the superscript "MAGICC" represents the data from MAGICC 6, and the global CO_2 emissions E_t for each RCP scenario are also given by MAGICC 6. Figure A1 shows that our calibrated carbon cycle can approximate well for all scenarios.

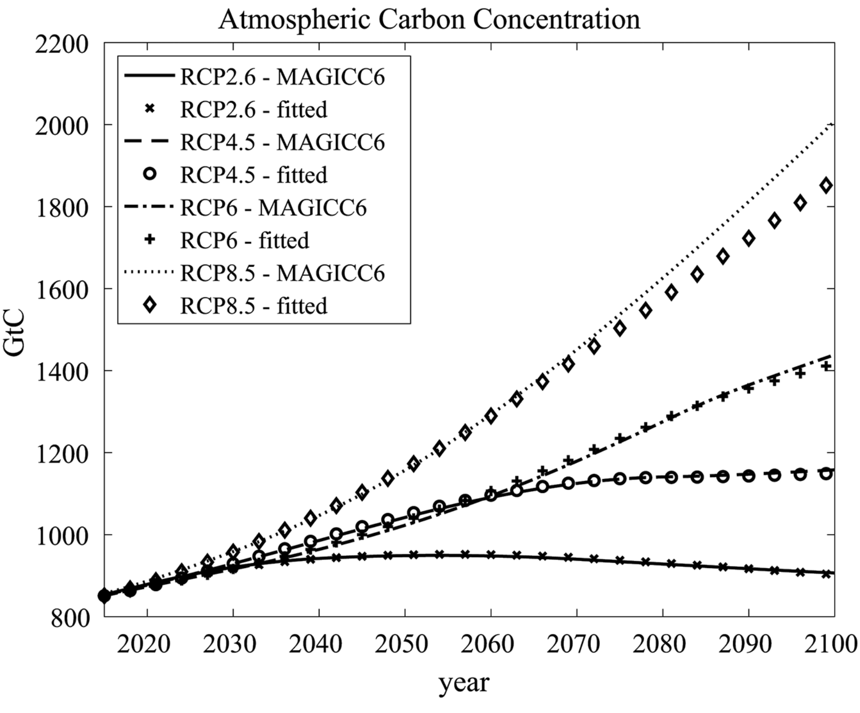

Figure A1. Fitting the carbon cycle to match RCP scenarios

A2. Solving the Open-Loop Nash Equilibrium

We follow Nordhaus and Yang (1996) and use an iterative method to solve the open-loop Nash equilibrium. We use the social planner's solution as the initial guess of two regional emission paths, denoted as $\{E_{t,i}^{\text{Ind},0} : t = 0, 1, \ldots T\}$ for economic region $i = 1, 2$, where $T = 500$ years. Now we assume that region 2's emission path is fixed at $E_{t,2}^{\text{Ind},0}$, and solve region 1's social planner problem:

$$\max_{c_{t,1},\mu_{t,1}} \sum_{t=0}^{\infty} \beta^t u(c_{t,1}) L_{t,1}, \tag{A3}$$

subject to the transition laws of three carbon concentration levels, four temperature levels, and its own regional capital, while the global emission is assumed to be

$$E_t = E_{t,1}^{\text{Ind}} + E_{t,2}^{\text{Ind},0} + E_t^{\text{Land}}.$$

Note that $E_{t,1}^{\text{Ind}}$ is endogenous but $E_{t,2}^{\text{Ind},0}$ is exogenous. The solution of $E_{t,1}^{\text{Ind}}$ is denoted $E_{t,1}^{\text{Ind},*}$. Similarly, we assume that region 1's emission path is fixed at $E_{t,1}^{\text{Ind},0}$, and solve region 2's social planner problem and obtain its solution of $E_{t,2}^{\text{Ind}}$, denoted $E_{t,2}^{\text{Ind},*}$. Now we let

$$E_{t,i}^{\text{Ind},1} = \omega E_{t,i}^{\text{Ind},*} + (1 - \omega) E_{t,i}^{\text{Ind},0}$$

for all t and i, where ω is chosen to be 0.5. Thus, we have updated the emission paths $\{E_{t,i}^{\text{Ind},0} : t = 0, 1, \ldots, T\}$ to $\{E_{t,i}^{\text{Ind},1} : t = 0, 1, \ldots, T\}$. Similarly we can use $\{E_{t,i}^{\text{Ind},1} : t = 0, 1, \ldots, T\}$ to generate $\{E_{t,i}^{\text{Ind},2} : t = 0, 1, \ldots, T\}$. Keep this process until the difference between $\{E_{t,i}^{\text{Ind},j} : t = 0, 1, \ldots, T\}$ and $\{E_{t,i}^{\text{Ind},j+1} : t = 0, 1, \ldots, T\}$ is small for both i, that is,

$$\max_{t,i} \frac{\left| E_{t,i}^{\text{Ind},j+1} - E_{t,i}^{\text{Ind},j} \right|}{1 + \left| E_{t,i}^{\text{Ind},j} \right|} < \epsilon.$$

In our case, we use $\epsilon = 10^{-6}$ as the stopping criterion.

A3. Variables and Values of Parameters

In our model, we approximate the land carbon emissions E_t^{Land} and exogenous radiative forcing by the annual analogs of the corresponding paths of DICE-2016R (in five-year time steps) as follows:

$$E_t^{\text{Land}} = 0.95 e^{-0.115t} \tag{A4}$$

$$F_t^{\text{EX}} = \begin{cases} 0.5 + 0.00588t, & \text{if } t \leq 85 \\ 1, & \text{otherwise.} \end{cases} \tag{A5}$$

We follow Cai et al. (2019) and specify the abatement costs and the carbon intensities:

$$\theta_{1,t,i} = b_{0,i} \exp\left(-\alpha_i^b t\right) \sigma_{t,i}/\theta_2$$

$$\sigma_{t,i} = \sigma_{0,i} \exp(-\alpha_i^\sigma (1 - \exp(-d_i^\sigma t))/d_i^\sigma).$$

Table A1 lists the values and/or definition of all parameters, variables, and symbols in the climate system. Tables A2–A3 list the values and/or definition of all parameters, variables, and symbols in the economic system.

Table A1. Parameters, Variables, and Symbols in the Climate System

t	Time in years ($t = 0$ represents year 2015)
$i \in \{1, 2, 3\}$	Region i (for the climate system: North $i = 1$, Tropics $i = 2$, South $i = 3$; for the economic system: North $i = 1$, Tropics/South $i = 2$)
M_t^{AT}	Carbon concentration in the atmosphere (billion tons); $M_0^{\mathrm{AT}} = 851$
M_t^{UO}	Carbon concentration in upper ocean (billion tons); $M_0^{\mathrm{UO}} = 460$
M_t^{DO}	Carbon concentration in deep ocean (billion tons); $M_0^{\mathrm{DO}} = 1740$
$\mathbf{M}_t = (M_t^{\mathrm{AT}}, M_t^{\mathrm{UO}}, M_t^{\mathrm{DO}})^\top$	Carbon concentration vector
$T_{t,i}^{\mathrm{AT}}$	Regional atmospheric temperature increase above preindustrial level (Celsius); $T_{0,1}^{\mathrm{AT}} = 1.29$, $T_{0,2}^{\mathrm{AT}} = .91$, $T_{0,3}^{\mathrm{AT}} = .79$
T_t^{OC}	Average ocean temperature increase (Celsius); $T_0^{\mathrm{OC}} = .1$
$(T_{t,1}^{\mathrm{AT}}, T_{t,2}^{\mathrm{AT}}, T_{t,3}^{\mathrm{AT}}, T_t^{\mathrm{OC}})$	Temperature vector
F_t	Global radiative forcing
F_t^{EX}	Exogenous radiative forcing
$\eta = 3.68$	Radiative forcing parameter
$\mathbf{\Phi}_{\mathrm{M}}$	Transition matrix of carbon cycle
$\mathbf{\Phi}_{\mathrm{T}}$	Transition matrix of temperature system
$\phi_{1,2} = .0597$, $\phi_{2,3} = .012$	Parameters in transition matrix of carbon cycle
$(M_*^{\mathrm{AT}}, M_*^{\mathrm{UO}}, M_*^{\mathrm{DO}}) =$ (588, 360, 1720)	Preindustrial carbon concentration
$\xi_1 = .037$, $\xi_2 = .034$ $\xi_3 = .0006$, $\xi_4 = .011$ $\xi_5 = .061$, $\xi_6 = .04$ $\xi_7 = .0088$, $\xi_{\mathrm{ECS}} = 3.1$	Parameters in transition matrix of temperature system

Table A2. Parameters, Variables, and Symbols in the Economic System

$Y_{t,i}$	Gross output
$A_{t,i}$	Total productivity factor (TFP); $A_{0,1} = 6.724$, $A_{0,2} = 2.054$
$\zeta_{1,1}^{\mathrm{TFP}} = .0169$, $\zeta_{1,2}^{\mathrm{TFP}} = .0122$	Parameters for TFP of the North under no climate impact
$\zeta_{2,1}^{\mathrm{TFP}} = .0385$, $\zeta_{2,2}^{\mathrm{TFP}} = .0197$	Parameters for TFP of the Tropics/South under no climate impact
$L_{t,i}$	Population (in billions)
$K_{t,i}$	Capital (in $ trillions); $K_{0,1} = 100$, $K_{0,2} = 53$
$\alpha = .3$	Output elasticity of capital
$\Psi_{t,i}$	Mitigation expenditure
$\mu_{t,i}$	Emission control rate
E_t, $E_{t,i}^{\mathrm{Ind}}$, E_t^{Land}	Global emission; regional industrial emission; land emission
$\sigma_{t,i}$	Carbon intensity; $\sigma_{0,1} = .119$, $\sigma_{0,2} = .132$
$\alpha_1^\sigma = .0156$, $\alpha_2^\sigma = .0063$	Initial declining rate of carbon intensity
$d_1^\sigma = .0181$, $d_2^\sigma = .000698$	Change rate of declining rate of carbon intensity
$\theta_2 = 2.8$, $\theta_3 = .01$	Mitigation cost parameter
$\theta_{1,t,i}$	Adjusted cost for backstop
$\mathrm{b}_{0,1} = 1.32$, $\mathrm{b}_{0,1} = 1.68$	Initial backstop price
$\alpha_1^b = \alpha_2^b = .005$	Declining rate of backstop price
$\delta_K = .1$	Annual depreciation rate of capital
$c_{t,i}$	Per capita consumption
$\gamma = 1.45$	Elasticity of marginal utility
u	Per capita utility function
$\beta = .985$	Discount factor

Table A3. TFP Parameters for Climate Impact in the Six Cases

	North			Tropics/South		
	$\zeta_{1,3}^{\mathrm{TFP}}$	$\zeta_{1,4}^{\mathrm{TFP}}$	δ_1^{TFP}	$\zeta_{2,3}^{\mathrm{TFP}}$	$\zeta_{2,4}^{\mathrm{TFP}}$	δ_2^{TFP}
Case 1	.0088	.0036	.557	.047	.074	.695
Case 2	.0032	.038		.386	.407	
Case 3	−.018	.02	.573	.048	.04	.694
Case 4	.045	.065		.248	.24	
Case 5	.04	.045	.5	.047	.082	.708
Case 6	.06	.372		.343	.299	

A4. Additional Results

We do a sensitivity analysis over the declining rate of the exogenous TFP growth, that is, $\zeta_{i,2}^{\mathrm{TFP}}$. Figure A2 displays the regional SCC in the three cases with persistent climate impact (cases 2, 4, and 6) under cooperation or noncooperation, assuming that the value of $\zeta_{i,2}^{\mathrm{TFP}}$ is half of its calibrated value listed in table A2 for each economic region i. We see that the growth of the SCC in each of cases 2, 4, and 6 is not decreasing toward the end of this century and is much larger than the solution with the calibrated values of $\zeta_{i,2}^{\mathrm{TFP}}$ shown in figure 8. This happens because a smaller $\zeta_{i,2}^{\mathrm{TFP}}$ implies a slower convergence rate of the exogenous TFP growth (i.e., $g_{i,t}^{\mathrm{TFP,EX}}$) to zero as $t \to \infty$, then a larger impact from the temperature anomaly on TFP levels according to (14).

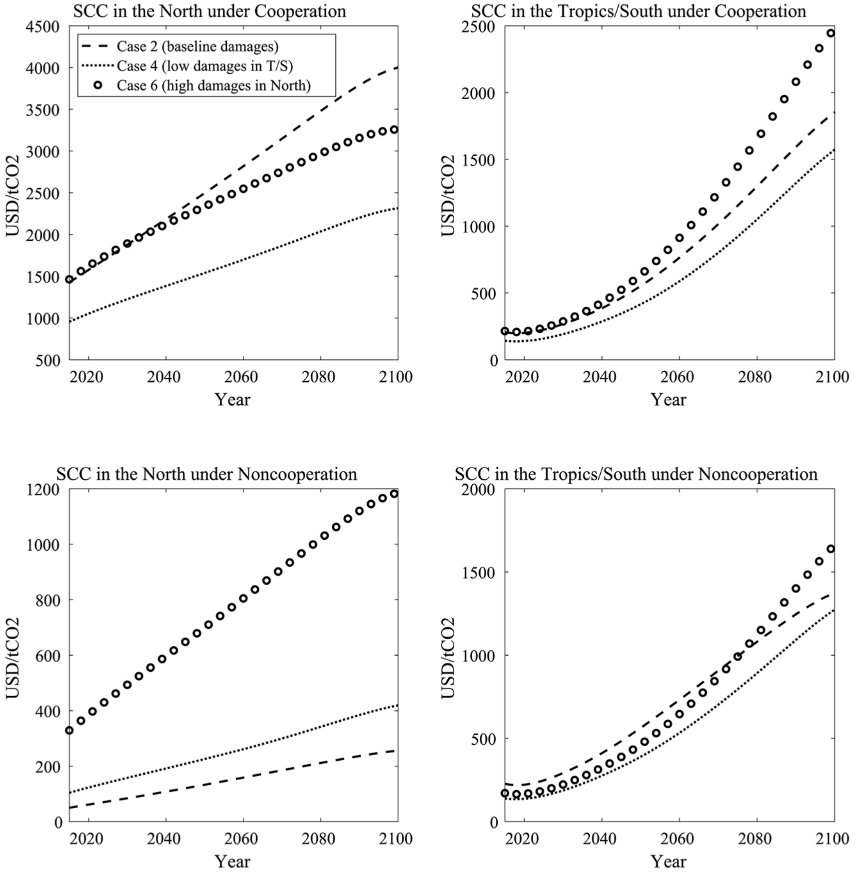

Figure A2. Regional SCC in the three cases with persistent climate impact (cases 2, 4, and 6) under cooperation or noncooperation, assuming that the value of $\zeta_{i,2}^{\mathrm{TFP}}$ is half of its calibrated value for each economic region i.

REFERENCES

Acemoglu, Daron, Ufuk Akcigit, Douglas Hanley, and William Kerr. 2016. Transition to clean technology. *Journal of Political Economy* 124 (1): 52–104.

Auffhammer, Maximilian. 2018. Quantifying economic damages from climate change. *Journal of Economic Perspectives* 32 (4): 33–52.

Baker, Erin, Valentina Bosetti, and Ahti Salo. 2020. Robust portfolio decision analysis: An application to the energy research and development portfolio problem. *European Journal of Operational Research* 284 (3): 1107–20.

Baldwin, Elizabeth, Yongyang Cai, and Karlygash Kuralbayeva. 2020. To build or not to build? Capital stocks and climate policy. *Journal of Environmental Economics and Management* 100, article 102235.

Barnett, Michael, William Brock, and Lars Peter Hansen. 2020. Pricing uncertainty induced by climate change. *Review of Financial Studies* 33 (3): 1024–66.

———. 2021. Climate change uncertainty spillover in the macroeconomy. Working paper 29064, National Bureau of Economic Research, Cambridge, MA.

Barreca, Alan, Karen Clay, Olivier Deschenes, Michael Greenstone, and Joseph S. Shapiro. 2016. Adapting to climate change: The remarkable decline in the US temperature-mortality relationship over the twentieth century. *Journal of Political Economy* 124 (1): 105–59.

Brock, William, and Anastasios Xepapadeas. 2017. Climate change policy under polar amplification. *European Economic Review* 94:263–82.

———. 2019. Regional climate change policy under positive feedbacks and strategic interactions. *Environmental and Resource Economics* 72 (1): 51–75.

Burke, Marshall, W. Matthew Davis, and Noah S. Diffenbaugh. 2018. Large potential reduction in economic damages under UN mitigation targets. *Nature* 557 (7706): 549–53.

Burke, Marshall, Solomon M. Hsiang, and Edward Miguel. 2015a. Climate and conflict. *Annual Review of Economics* 7 (1): 577–617.

———. 2015b. Global non-linear effect of temperature on economic production. *Nature* 527 (7577): 235–39.

Cai, Yongyang. 2021. The role of uncertainty in controlling climate change. *Oxford Research Encyclopedia of Economics and Finance*. https://doi.org/10.1093/acrefore/9780190625979.013.573.

Cai, Yongyang, William Brock, Anastasios Xepapadeas, and Kenneth L. Judd. 2019. Climate policy under spatial heat transport: Cooperative and noncooperative regional outcomes. arXiv preprint 1909.04009. https://arxiv.org/abs/1909.04009.

Cai, Yongyang, Kenneth L. Judd, and Thomas S. Lontzek. 2017. The social cost of carbon with economic and climate risks. Hoover economics working paper 18113, Hoover Institution, Washington, DC.

Cai, Yongyang, Timothy M. Lenton, and Thomas S. Lontzek. 2016. Risk of multiple interacting tipping points should encourage rapid CO_2 emission reduction. *Nature Climate Change* 6 (5): 520–25.

Cai, Yongyang, and Thomas S. Lontzek. 2019. The social cost of carbon with economic and climate risks. *Journal of Political Economy* 6:2684–2734.

Campiglio, Emanuele, Simon Dietz, and Frank Venmans. 2022. Optimal transition to a low-carbon economy. Working paper.

Carleton, Tamma A., and Solomon M. Hsiang. 2016. Social and economic impacts of climate. *Science* 353 (6304).

Dell, Melissa, Benjamin F. Jones, and Benjamin A. Olken. 2012. Temperature shocks and economic growth: Evidence from the last half century. *American Economic Journal: Macroeconomics* 4 (3): 66–95.

Dennig, Francis, Mark B. Budolfson, Marc Fleurbaey, Asher Siebert, and Robert H. Socolow. 2015. Inequality, climate impacts on the future poor, and carbon prices. *Proceedings of the National Academy of Sciences* 112 (52): 15827–32.

Desmet, Klaus, Robert E. Kopp, Scott A. Kulp, David Krisztian Nagy, Michael Oppenheimer, Esteban Rossi-Hansberg, and Benjamin H. Strauss. 2021. Evaluating the economic cost of coastal flooding. *American Economic Journal: Macroeconomics* 13 (2): 444–86.

Desmet, Klaus, and Esteban Rossi-Hansberg. 2015. On the spatial economic impact of global warming. *Journal of Urban Economics* 88:16–37.

Dietz, Simon, James Rising, Thomas Stoerk, and Gernot Wagner. 2021. Economic impacts of tipping points in the climate system. *Proceedings of the National Academy of Sciences* 118 (34): e2103081118.

Dietz, Simon, and Nicholas Stern. 2015. Endogenous growth, convexity of damage and climate risk: How Nordhaus' framework supports deep cuts in carbon emissions. *Economic Journal* 125 (583): 574–620.

Dietz, Simon, Frederick van der Ploeg, Armon Rezai, and Frank Venmans. 2021. Are economists getting climate dynamics right and does it matter? *Journal of the Association of Environmental and Resource Economists* 8 (5): 895–921.

Dietz, Simon, and Frank Venmans. 2019. Cumulative carbon emissions and economic policy: In search of general principles. *Journal of Environmental Economics and Management* 96:108–29.

Diffenbaugh, Noah S., and Marshall Burke. 2019. Global warming has increased global economic inequality. *Proceedings of the National Academy of Sciences* 116 (20): 9808–13.

Dutta, Prajit K., and Roy Radner. 2009. A strategic analysis of global warming: Theory and some numbers. *Journal of Economic Behavior and Organization* 71 (2): 187–209.

Gillingham, Kenneth, and James H. Stock. 2018. The cost of reducing greenhouse gas emissions. *Journal of Economic Perspectives* 32 (4): 53–72.

Golosov, Mikhail, John Hassler, Per Krusell, and Aleh Tsyvinski. 2014. Optimal taxes on fossil fuel in general equilibrium. *Econometrica* 82 (1): 41–88.

Hambel, Christoph, Holger Kraft, and Eduardo Schwartz. 2021. The social cost of carbon in a noncooperative world. *Journal of International Economics* 131:103490.

Hassler, John, and Per Krusell. 2012. Economics and climate change: Integrated assessment in a multiregion world. *Journal of the European Economic Association* 10 (5): 974–1000.

Heal, Geoffrey, and Jisung Park. 2016. Reflections—temperature stress and the direct impact of climate change: A review of an emerging literature. *Review of Environmental Economics and Policy* 10 (2): 347–62.

Hsiang, Solomon, Robert Kopp, Amir Jina, James Rising, Michael Delgado, Shashank Mohan, D. J. Rasmussen, et al. 2017. Estimating economic damage from climate change in the United States. *Science* 356 (6345): 1362–69.

Jaakkola, Niko, and Frederick van der Ploeg. 2019. Non-cooperative and cooperative climate policies with anticipated breakthrough technology. *Journal of Environmental Economics and Management* 97:42–66.

Kahn, Matthew E., Kamiar Mohaddes, Ryan N. C. Ng, M. Hashem Pesaran, Mehdi Raissi, and Jui-Chung Yang. 2021. Long-term macroeconomic effects of climate change: A cross-country analysis. *Energy Economics* 104:105624.

Kalkuhl, Matthias, and Leonie Wenz. 2020. The impact of climate conditions on economic production: Evidence from a global panel of regions. *Journal of Environmental Economics and Management* 103:102360.

KC, Samir, and Wolfgang Lutz. 2017. The human core of the shared socioeconomic pathways: Population scenarios by age, sex and level of education for all countries to 2100. *Global Environmental Change* 42:181–92.

Kolstad, Charles D., and Frances C. Moore. 2020. Estimating the economic impacts of climate change using weather observations. *Review of Environmental Economics and Policy* 14 (1): 1–24.

Kortum, Samuel S., and David A. Weisbach. 2021. Optimal unilateral carbon policy. SSRN Scholarly paper 3958930. https://papers.ssrn.com/abstract=3958930.

Krusell, Per, and Anthony Smith. 2017. Climate change around the world. Meeting paper, Society for Economic Dynamics.

Langen, Peter L., and Vladimir A. Alexeev. 2007. Polar amplification as a preferred response in an idealized aquaplanet GCM. *Climate Dynamics* 29 (2): 305–17.

Leduc, Martin, H. Damon Matthews, and Ramon de Elia. 2016. Regional estimates of the transient climate response to cumulative CO_2 emissions. *Nature Climate Change* 6 (5): 474–78.

Mach, Katharine J., Caroline M. Kraan, W. Neil Adger, Halvard Buhaug, Marshall Burke, James D. Fearon, Christopher B. Field, et al. 2019. Climate as a risk factor for armed conflict. *Nature* 571 (7764): 193–97.

Mattauch, Linus, H. Damon Matthews, Richard Millar, Armon Rezai, Susan Solomon, and Frank Venmans. 2020. Steering the climate system: Using inertia to lower the cost of policy; Comment. *American Economic Review* 110 (4): 1231–37.

Matthews, H. Damon, Nathan P. Gillett, Peter A. Stott, and Kirsten Zickfeld. 2009. The proportionality of global warming to cumulative carbon emissions. *Nature* 459 (7248): 829–32.

Meinshausen, M., S. C. B. Raper, and T. M. L. Wigley. 2011. Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6: Part I, Model description and calibration. *Atmospheric Chemistry and Physics* 11:1417–52.

Meinshausen, M., S. J. Smith, K. Calvin, J. S. Daniel, M. L. T. Kainuma, J-F. Lamarque, K. Matsumoto, et al. 2011. The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. *Climatic Change* 109:213–41.

Moore, Frances C., and Delavane B. Diaz. 2015. Temperature impacts on economic growth warrant stringent mitigation policy. *Nature Climate Change* 5 (2): 127–31.

Moyer, Elisabeth J., Mark D. Woolley, Nathan J. Matteson, Michael J. Glotter, and David A. Weisbach. 2014. Climate impacts on economic growth as drivers of uncertainty in the social cost of carbon. *Journal of Legal Studies* 43 (2): 401–25.

Navarro-Racines, Carlos, Jaime Tarapues, Philip Thornton, Andy Jarvis, and Julian Ramirez-Villegas. 2020. High-resolution and bias-corrected CMIP5 projections for climate change impact assessments. *Scientific Data* 7 (1): 7.

Neumann, James E., Jacqueline Willwerth, Jeremy Martinich, James McFarland, Marcus C. Sarofim, and Gary Yohe. 2020. Climate damage functions for estimating the economic impacts of climate change in the United States. *Review of Environmental Economics and Policy* 14 (1): 25–43.

Newell, Richard G., Brian C. Prest, and Steven E. Sexton. 2021. The GDP-temperature relationship: Implications for climate change damages. *Journal of Environmental Economics and Management* 108:102445.

Nordhaus, William D. 2008. *A question of balance: Weighing the options on global warming policies*. New Haven, CT: Yale University Press.

———. 2010. Economic aspects of global warming in a post-Copenhagen environment. *Proceedings of the National Academy of Sciences* 107 (26): 11721–26.

———. 2017. Revisiting the social cost of carbon. *Proceedings of the National Academy of Sciences* 114 (7): 1518–23.

Nordhaus, William D., and Zili Yang. 1996. A regional dynamic general equilibrium model of alternative climate change strategies. *American Economic Review* 86 (4): 741–65.

Rezai, Armon, Lance Taylor, and Duncan Foley. 2018. Economic growth, income distribution, and climate change. *Ecological Economics* 146:164–72.

Riahi, Keywan, Detlef P. van Vuuren, Elmar Kriegler, Jae Edmonds, Brian C. O'Neill, Shinichiro Fujimori, Nico Bauer, et al. 2017. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change* 42:153–68.

Ricke, Katharine, Laurent Drouet, Ken Caldeira, and Massimo Tavoni. 2018. Country-level social cost of carbon. *Nature Climate Change* 8 (10): 895–900.

Ueckerdt, Falko, Katja Frieler, Stefan Lange, Leonie Wenz, Gunnar Luderer, and Anders Levermann. 2019. The economically optimal warming limit of the planet. *Earth System Dynamics* 10 (4): 741–63.

van der Ploeg, Frederick. 2018. The safe carbon budget. *Climatic Change* 147 (1): 47–59.

van der Ploeg, Frederick, and Aart de Zeeuw. 2016. Non-cooperative and cooperative responses to climate catastrophes in the global economy: A north-south perspective. *Environmental and Resource Economics* 65 (3): 519–40.

Weitzman, Martin L. 2012. GHG targets as insurance against catastrophic climate damages. *Journal of Public Economic Theory* 14 (2): 221–44.

Wunsch, Carl. 2005. The total meridional heat flux and its oceanic and atmospheric partition. *Journal of Climate* 18 (21): 4374–80.