Virtual Seminar on Climate Economics

Federal Reserve Bank of San Francisco

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The Economic Geography of Global Warming

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An Economic Assessment Model

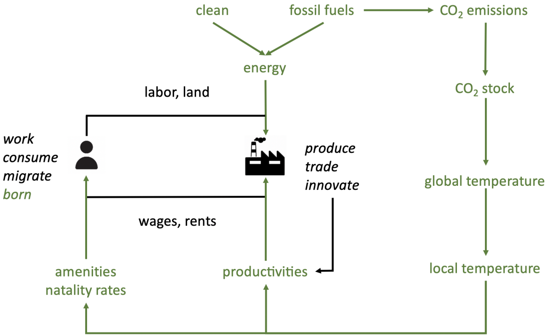
- Global warming is a **protracted**, **global**, phenomenon with **heterogeneous local effects**
- Standard climate models use loss functions relating aggregate economic outcomes to climate variables
  - Fail to incorporate behavioral responses, and therefore economic adaptation
  - Ignore the vast spatial heterogeneity in climate damages
- We propose and quantify a spatial and dynamic assessment model
  - Emphasizing the role of **economic adaptation through migration, trade, and innovation**

Literature Review

- Empirical Estimates of Climate Damages
  - Albouy et al. (2016), Barreca et al. (2016), Dell et al. (2012, 2014), Deschênes and Greenstone (2007, 2012), Greenstone et al. (2020), Nordhaus (2006), Schlenker and Roberts (2009)
- Economic Models of Climate Change
  - Acemoglu et al. (2012, 2016, 2019), Aghion et al. (2016), Anthoff and Tol [FUND] (2014), Golosov et al. (2014), Hassler et al. (2016, 2019, 2020), Hope [PAGE] (2019), IPCC (2013), Nordhaus et al. [DICE, RICE] (1993, 1996, 2000, 2016), Stern (2012)
- Spatial Dynamic Models
  - Caliendo et al. (2019) Desmet and Rossi-Hansberg (2013, 2014), Desmet et al. (2018)
- Incipient literature in this intersection
  - Balboni (2019), Desmet and Rossi-Hansberg (2015), Desmet et al. (2018), Krusell and Smith (2018)

Model Characteristics

- We extend the spatial growth model in Desmet et al., (2018)
  - Add natality, energy, carbon cycle, and local temperature effect on amenities and productivities



  - Quantify using $1^\circ \times 1^\circ$ G-Econ data on population and income in 2000
  - Set trade and mobility frictions to match gravity and net migration flows

Model: Preferences

- Agent's period utility:

$$u_t^i(\bar{r}_-, r) = \underbrace{\left[\int_0^1 c_t^\omega(r)^\rho d\omega\right]^{1/\rho}}_{\text{consumption}} \underbrace{\boldsymbol{b_t(r)}\varepsilon_t^i(r)}_{\text{amenities}} \underbrace{\prod_{\ell=1}^{t} m(r_{\ell-1}, r_\ell)^{-1}}_{\text{moving costs}}$$

  - Local amenities are affected by:
    - Congestion due to population density, $b_t(r) = \boldsymbol{\bar{b}_t(r)} L_t(r)^{-\lambda}$
    - Local temperature changes $\Delta T_t(r)$ through function $\Lambda^b(\cdot)$

$$\underbrace{\bar{b}_t(r)}_{\substack{\text{fundamental} \\ \text{amenities}}} = \boldsymbol{\left(1 + \Lambda^b(\Delta T_t(r), T_{t-1}(r))\right)} \bar{b}_{t-1}(r)$$

  - Migration costs are reversible moving costs

Model: Natality

- Spatial equilibrium yields local population, $H(r)L_t(r)$
- Each agent in r at end of period t has $n_t(r)$ offsprings
  - Local population before migration is given by

$$\underbrace{H(r)L'_{t+1}(r)}_{\substack{\text{population at } t+1 \\ \text{before mobility}}} = (1 + \boldsymbol{n_t(r)})\underbrace{H(r)L_t(r)}_{\substack{\text{population at } t \\ \text{after mobility}}}$$

  - Global population L_{t+1} evolves according to

$$L_{t+1} = \int_S H(v)L'_{t+1}(v)dv$$

  - Natality rates depend on real income, $y_t(r)$, and temperature, $T_t(r)$

Model: Technology

- Production function of variety $\omega \in [0,1]$ per land unit details

$$q_t^\omega(r) = \underbrace{\phi_t^\omega(r)^{\gamma_1}}_{\text{innovation}} \underbrace{z_t^\omega(r)}_{\text{productivity draw}} \left(\underbrace{L_t^\omega(r)^\chi}_{\text{labor}} \underbrace{e_t^\omega(r)^{1-\chi}}_{\text{energy}} \right)^\mu$$

  - Level of productivity draws, $z_t^\omega(r)$, is given by $a_t(r)$
  - Local productivities are affected by:
    - ⋆ Agglomeration due to population density, $a_t(r) = \bar{a}_t(r) L_t(r)^\alpha$
    - ⋆ Innovation, diffusion and temperature

$$\begin{aligned} a_t(r) &= \bar{a}_t(r) L_t(r)^\alpha \\ \bar{a}_t(r) &= \left(1 + \Lambda^a(\Delta T_t(r), T_{t-1}(r))\right) \\ &\quad \times \phi_{t-1}(r)^{\theta\gamma_1} \left[\int \mathcal{D}(r,v) \bar{a}_{t-1}(v) dv \right]^{1-\gamma_2} \bar{a}_{t-1}(r)^{\gamma_2} \end{aligned}$$

Model: Energy

- CES energy composite between **fossil fuels** and **clean sources**

$$e_t^{\omega}(r) = \left(\kappa \underbrace{\boldsymbol{e_t^{f,\omega}(r)}^{\frac{\epsilon-1}{\epsilon}}}_{\text{fossil fuels}} + (1-\kappa)\underbrace{\boldsymbol{e_t^{c,\omega}(r)}^{\frac{\epsilon-1}{\epsilon}}}_{\text{clean sources}}\right)^{\frac{\epsilon}{\epsilon-1}}$$

- One unit of energy costs $\mathcal{Q}_t^j(r)$ units of labor

$$\mathcal{Q}_t^f(r) = \frac{f(CumCO2_t)}{\zeta_t^f(r)}, \quad \mathcal{Q}_t^c(r) = \frac{1}{\zeta_t^c(r)}$$

  - $f(\cdot)$ denotes extraction cost given cumulative CO_2, $CumCO2_t$
  - $\zeta_t^j(r)$ is energy j's productivity, given by

$$\zeta_t^j(r) = \left(\frac{y_t^w}{y_{t-1}^w}\right)^{\upsilon^j} \zeta_{t-1}^j(r), \quad j \in \{f, c\}$$

Model: Trade

- Local diffusion of technology and competition in land prices
  - Dynamic profit maximization simplifies to static problems expl
- Trade balance region by region and iceberg trade costs
  - Gravity equation for bilateral trade flows details

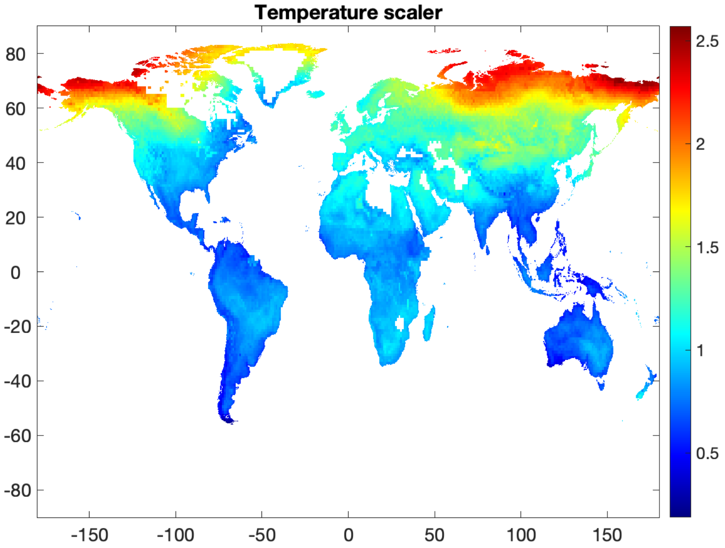
Model: Climate

- CO_2 emissions rise global temperature (IPCC, 2013) model
  - Endogenous evolution of CO_2 from fossil fuel combustion
  - Exogenous CO_2 from forestry and non-CO_2 GHG (RCP 8.5)
- Linear relation from global T_t to local temperature $T_t(r)$ (Mitchell, 2003)

$$T_{t+1}(r) = T_t(r) + g(r) \cdot (T_{t+1} - T_t)$$

  - $g(\cdot)$ is a function of geographical attributes for each cell
    - ⋆ Chebyshev polynomial of order 10 on latitude, longitude, elevation, distance to coast, distance to ocean, distance to water, vegetation density and albedo
  - Data from Berkeley Earth Surface Temperature and NASA Earth Observations

Model: Temperature Downscaling



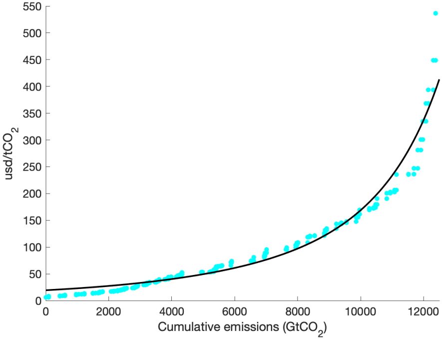
Estimation: Summary

- Baseline estimation from Desmet et al. (2018) table
- Estimation of additional parameters

1. Energy: $q_t^\omega(r) = \phi_t^\omega(r)^{\gamma_1} z_t^\omega(r) \left(L_t^\omega(r)^{\chi} e_t^\omega(r)^{1-\chi}\right)^\mu$, $e_t^\omega(r) = (\kappa e_t^{f,\omega}(r)^{\frac{\epsilon-1}{\epsilon}} + (1-\kappa) e_t^{c,\omega}(r)^{\frac{\epsilon-1}{\epsilon}})^{\frac{\epsilon}{\epsilon-1}}$	
$\mathcal{Q}_t^f(r) = f(CumCO2_t)/\zeta_t^f(r)$, $\mathcal{Q}_t^c(r) = 1/\zeta_t^c(r)$, $\zeta_t^j(r) = \left(y_t^w/y_{t-1}^w\right)^{\upsilon^j} \zeta_{t-1}^j(r)$	
$\chi = 0.958$	Relation between global GDP, CO_2 emissions flow and price
$\epsilon = 1.6$	Elasticity of substitution (Popp, 2014; Papageorgiou et al., 2017)
$\kappa = 0.89$	Relation between prices and quantities of fossil fuels and clean energy
$f(\cdot)$	Extraction costs (Rogner, 1997; Bauer et al., 2016)
$\zeta_0^f(\cdot), \zeta_0^c(\cdot)$	Target current cell-level energy use
$\upsilon^f = 0.95$	Target historical global CO_2 emissions
$\upsilon^c = 1.05$	Target historical global clean energy use
2. Damage functions: $\Lambda^a(\Delta T_t(r), T_t(r))$, $\Lambda^b(\Delta T_t(r), T_t(r))$, $n_t(r) = \eta(y_t(r), L_t(r))$	
$\Lambda^a(\cdot), \Lambda^b(\cdot)$	Relation between temperature and productivities and amenities
$\eta(\cdot)$	Relation between real GDP and temperature and natalities
3. Carbon cycle and climate	
$g(\cdot)$	IPCC (2013) and Statistical downscaling

Estimation: Extraction Cost

1. Parametrize extraction cost $f(\cdot)$



- ⋆ Data from Bauer et al. (2016)
- ⋆ $f(CumCO2) = \left(\frac{f_1}{f_2+\exp(-f_3(CumCO2-f_4))}\right) - \left(\frac{f_5}{CumCO2-maxCumCO2}\right)^3$
- ⋆ $maxCumCO2 =$19,500 $GtCO_2$ are total CO_2 reserves

2. Compute initial energy productivities $\zeta_0^f(r), \zeta_0^c(r)$ details map
   - Optimality condition between energy and labor
   - Require data on population, fossil fuels and clean energy
3. Estimate υ^f, υ^c plot
   - Target historical CO_2 emissions and clean energy

Estimation: Damage Functions

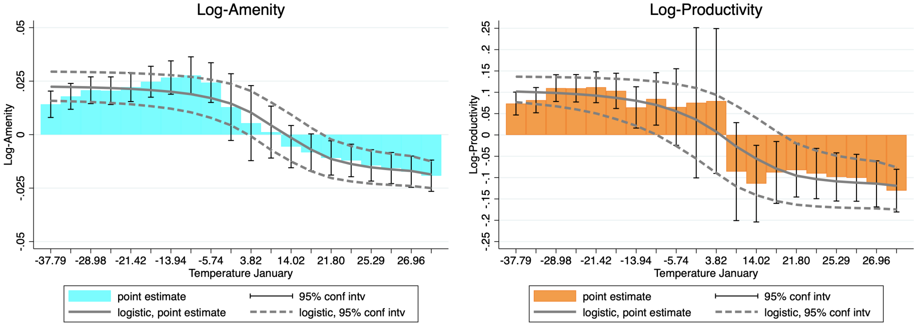
1. Retrieve fundamental amenities and productivities
   - Consistent with observed data (1990, 1995, 2000, 2005) details
2. Estimate damage function $\Lambda^b(\cdot), \Lambda^a(\cdot)$ on fundamentals

$$\log(b_t(r)) = \sum_{j=1}^{J} \boldsymbol{\delta_j^b} \cdot T_t(r) \cdot \mathbb{1}\{T_t(r) \in \mathcal{T}_j\} + \iota(b_i) + \iota_t(s_\ell) + \varepsilon_t(r)$$

$$\log(a_t(r)/\phi_t(r)) = \sum_{j=1}^{J} \boldsymbol{\delta_j^a} \cdot T_t(r) \cdot \mathbb{1}\{T_t(r) \in \mathcal{T}_j\} + \delta^z \cdot Z(r) + \iota_t(s_\ell) + \varepsilon_t(r)$$

   - $Z(r)$ controls for natural attributes
     - Elevation, distance to water, land type
   - $\iota(b_i)$ are block fixed effects
   - $\iota_t(s_\ell)$ are subnational-year fixed effects
   - $\varepsilon_t(r)$ are spatially correlated errors

Estimation: Damage Functions

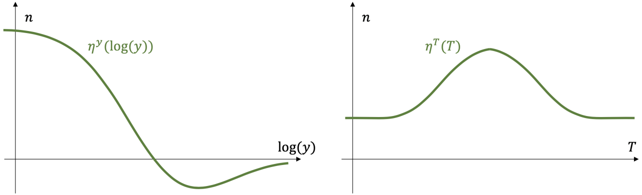


Estimation: Natality

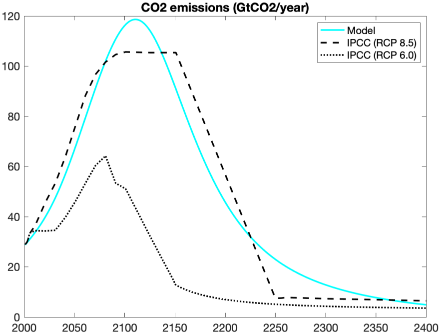
- Parametrize natality rate function $\eta(\cdot)$ details

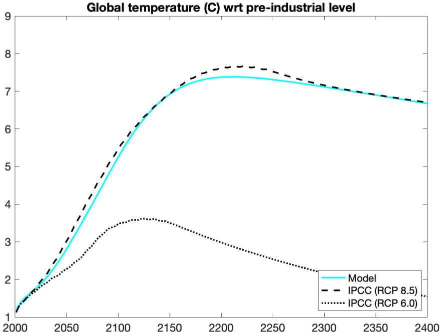
$$\eta\Big(\log(y_t(r)), T_t(r)\Big) = \eta^y\Big(\log(y_t(r))\Big) + \eta^T\Big(T_t(r), \log(y_t^w)\Big)$$

  - Natality rates decline as income rises (Delventhal et al., 2019)
    - ⋆ Natality converges to zero for a stable global population
  - Temperature minimizing mortality rates (Greenstone et al., 2018)
    - ⋆ Flatter responses as income rises (Barreca et al., 2016)
  - Coefficients of $\eta(\cdot)$ target historical country-level natality rates plot



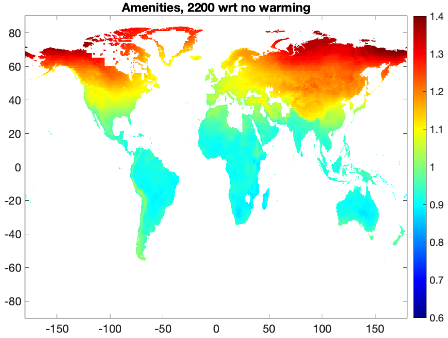
Baseline Scenario: CO2 Emissions and Global Temperature

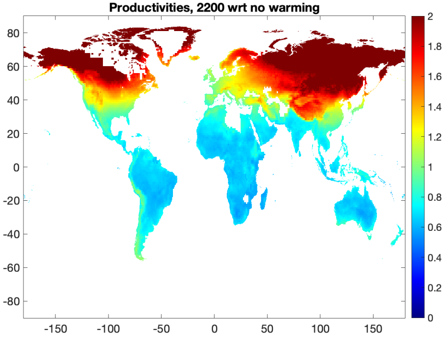




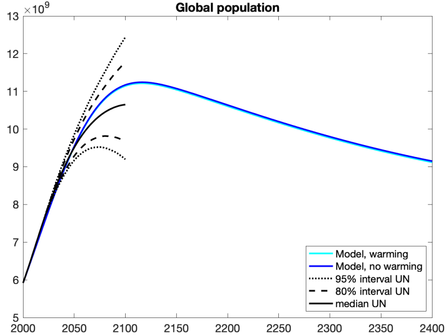
temperature

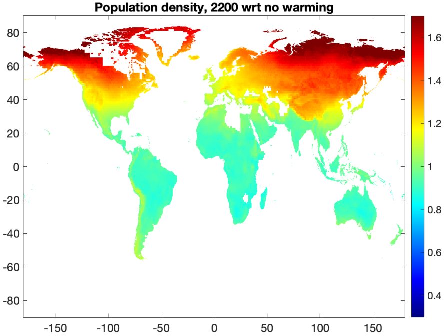
Baseline Scenario: Amenities and Productivities



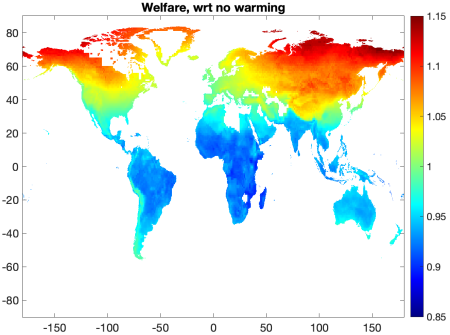


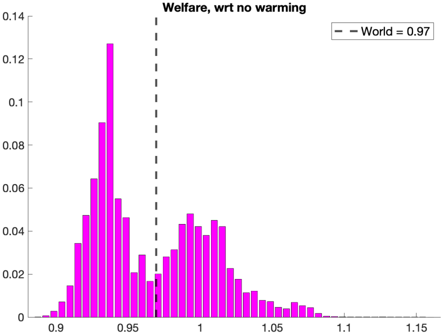
Baseline Scenario: Global and Local Population





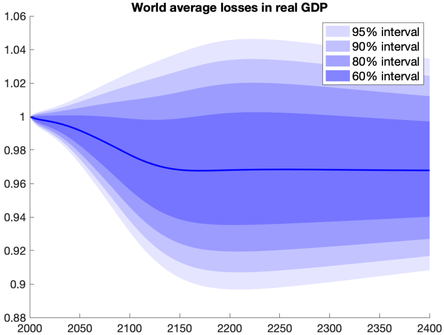
Baseline Scenario: Welfare Cost of Global Warming

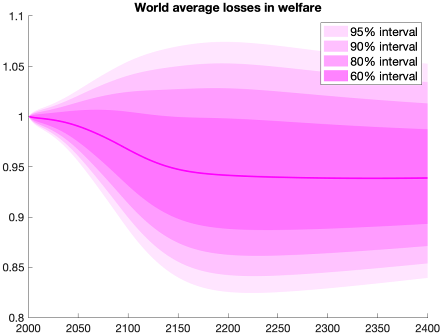




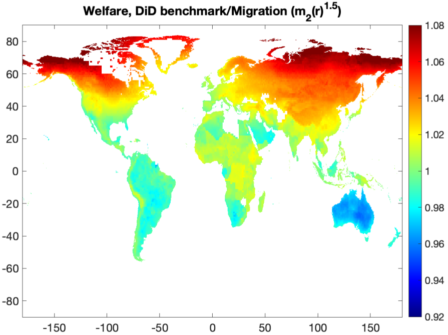
real GDP

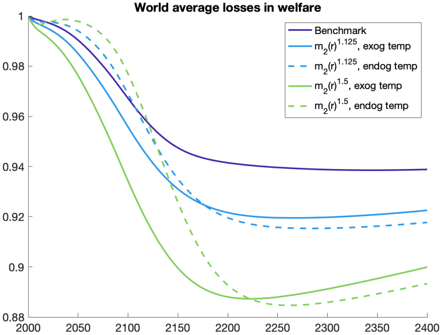
Baseline Scenario: Uncertainty about Damage Functions





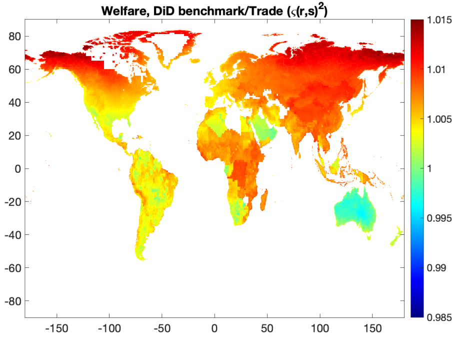
Adaptation: Migration

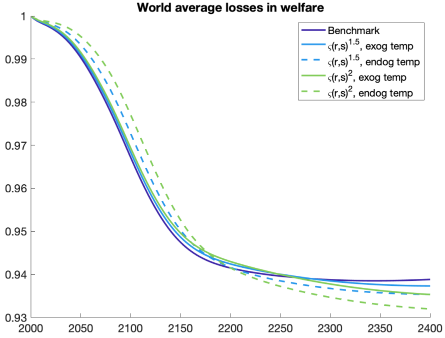




real GDP

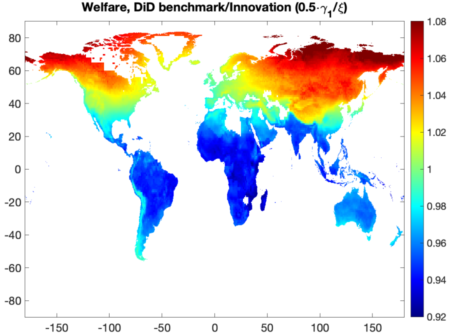
Adaptation: Trade

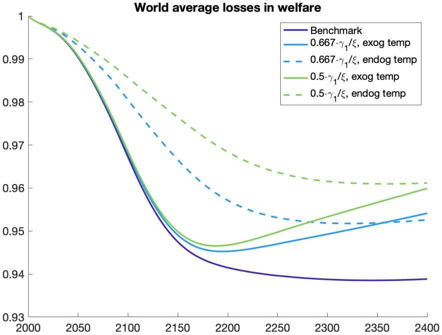




real GDP

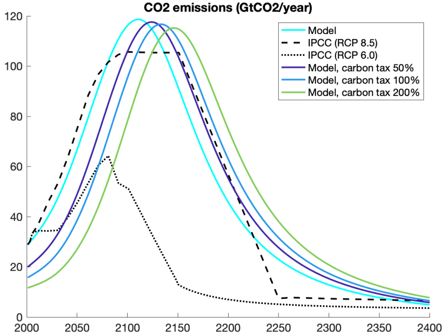
Adaptation: Innovation

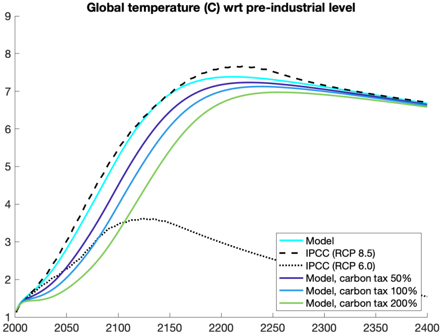




real GDP

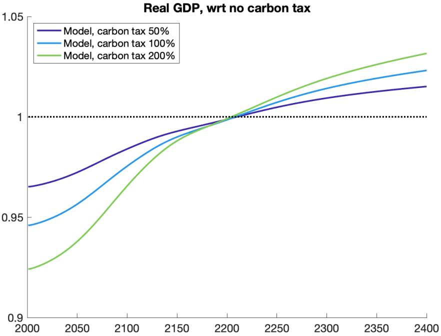
Carbon Taxes

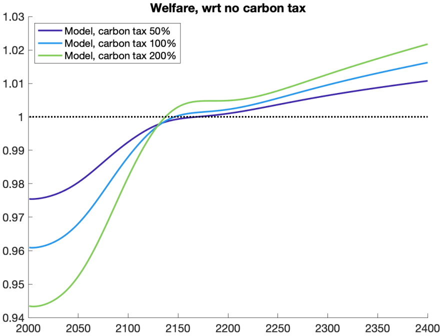




energy population

Carbon Taxes: Dynamic Effects

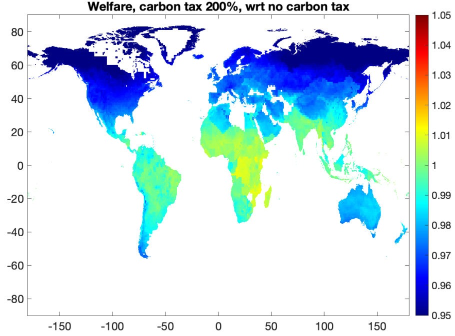


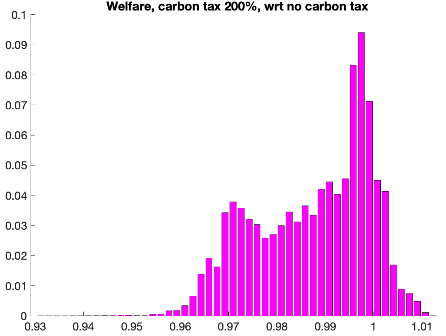


- Aggregate gains depend on discount factor and BGP growth rate

	Real GDP			Welfare		
	BGP gr	β=0.965	β=0.969	BGP gr	β=0.965	β=0.969
τ=50%	3.054%	0.991	1.020	3.015%	0.995	1.014
τ=100%	3.057%	0.986	1.032	3.017%	0.992	1.022
τ=200%	3.060%	0.980	1.046	3.019%	0.988	1.030

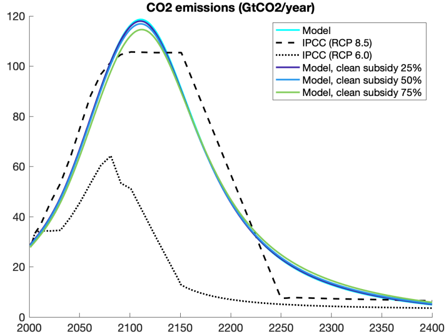
Carbon Taxes: Local Effects

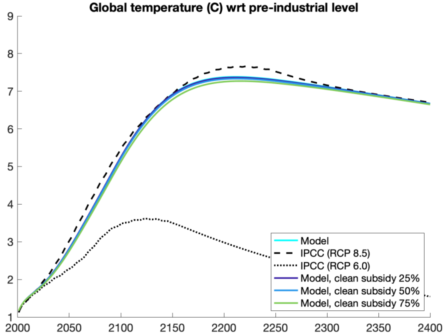




real GDP

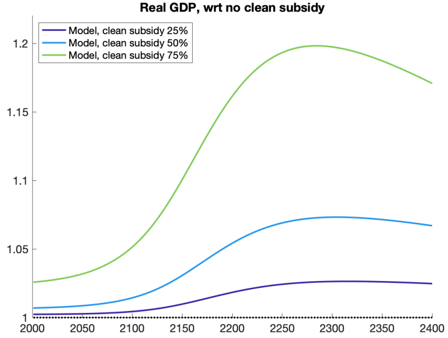
Clean Energy Subsidies

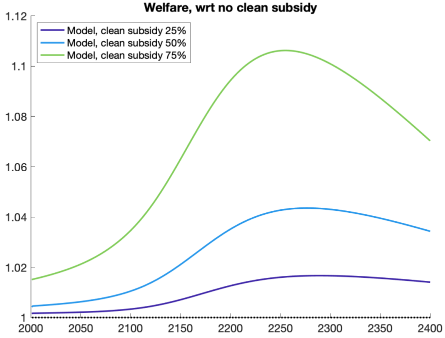




energy population taxes real GDP

Clean Energy Subsidies: Dynamic Effects

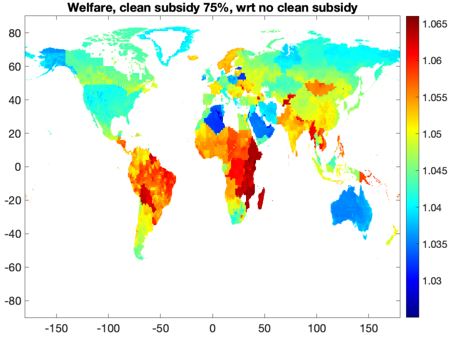


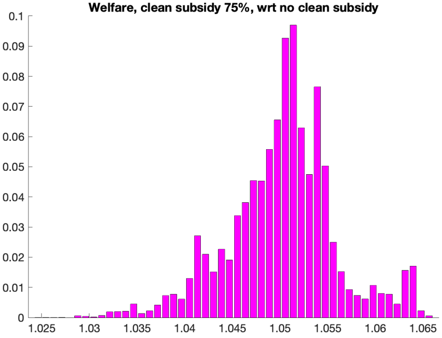


- Aggregate gains depend on discount factor and BGP growth rate

	Real GDP			Welfare		
	BGP gr	β=0.965	β=0.969	BGP gr	β=0.965	β=0.969
s=25%	3.047%	1.011	1.008	3.007%	1.007	1.002
s=50%	3.040%	1.033	1.020	2.999%	1.020	1.000
s=75%	3.018%	1.095	1.039	2.976%	1.051	0.984

Clean Energy Subsidies: Local Effects





real GDP

Conclusions

- We develop an economic spatial growth model of global warming
  - Accounts for **adaptation through trade, migration, innovation**
- Estimate impact of temperature on fundamentals
  - Heterogeneous spatial effect of temperature for amenities and productivities
- Large heterogeneity in climate damages over space
  - From welfare losses of 10% to gains of 15%
  - On average, welfare losses of 3%
  - Large role of adaptation, particularly migration
- Carbon taxes create trade-off between present and future benefit
  - Large disagreement across regions

Thank You

Model: Migration

- $\varepsilon_t^i(r)$ is location preference shock, iid(i,t,r) Fréchet back
- $m(r_{\ell-1}, r_\ell)$ is moving cost from $r_{\ell-1}$ to r_ℓ
  - Assume $m(r_{\ell-1}, r_\ell) = m_1(r_{\ell-1})m_2(r_\ell)$ and $m(r,r) = 1$
- Location decision in $t = 1$ only depends on current variables

$$
\begin{aligned}
\frac{V(r_0, \varepsilon_1^i)}{m_2(r_0)} &= \max_{r_1} \left[\frac{b_1(r_1)y_1(r_1)\varepsilon_1^i(r)}{m_2(r_1)} + \beta \frac{V(r_1, \varepsilon_2^i)}{m_2(r_1)} \right] \\
&= \max_{r_1} \frac{b_1(r_1)y_1(r_1)\varepsilon_1^i(r_1)}{m_2(r_1)} \\
&\quad + \beta \mathbb{E}\left[\max_{r_2} \frac{b_2(r_2)y_2(r_2)\varepsilon_2^i(r_2)}{m_2(r_2)} + \frac{V(r_2, \varepsilon_3^i)}{m_2(r_2)} \right]
\end{aligned}
$$

Model: Technology

- Endogenous dynamic process for local productivities back
  - $\phi_t^\omega(r)$ is innovation requiring $\nu\phi_t^\omega(r)^\xi$ labor units
  - $z_t^\omega(r)$ is idiosyncratic productivity
    - ⋆ iid(ω, t) Fréchet with shape θ and scale $a_t(r)^{1/\theta}$

$$a_t(r) = \bar{a}_t(r)L_t(r)^\alpha$$

$$\bar{a}_t(r) = \Big(1 + \Lambda^a(\Delta T_t(r), T_{t-1}(r))\Big) \times \phi_{t-1}(r)^{\theta\gamma_1} \left[\int \mathcal{D}(r,v)\bar{a}_{t-1}(v)dv\right]^{1-\gamma_2} \bar{a}_{t-1}(r)^{\gamma_2}$$

Model: Local Competition

- Dynamic problem reduces to sequence static problems back
  - Productivity draws are spatially correlated
    - ⋆ Perfectly correlated as distance tends to zero, and independent for large enough distances
  - In a small interval, continuum of firms that behave similarly
    - ⋆ Spatial correlation of productivities and continuity of amenities and transport costs
  - Firms compete in prices for land and profits are linear in land
    - ⋆ When interval size goes to zero, perfect competition for land
  - Firms innovate to raise land bid and bid up to zero profits
  - Firms take land bids by others as given
    - ⋆ Equilibrium land bid is also taken as given
    - ⋆ Labor, CO_2, clean energy and innovations are identical across varieties

Model: Trade

- Trade balance location by location back

$$w_t(r)L_t(r)H(r) = \int_S \pi_t(s,r)w_t(s)L_t(s)H(s)ds$$

$$\pi_t(s,r) = \frac{a_t(r)[mc_t(r)\varsigma(r,s)]^{-\theta}}{\int_S a_t(v)[mc_t(v)\varsigma(v,s)]^{-\theta}dv}$$

  - Technology draws $z_t^\omega(r)$ are iid(ω, t) Fréchet
    - With shape θ and scale $a_t(r)^{1/\theta}$
  - $\pi_t(s,r)$ is share of goods produced in r that are bought in s
  - $mc_t(r)$ is marginal cost in r
  - $\varsigma(s,r)$ is iceberg cost of transporting a goods from r to s

Model: Carbon Cycle

- Reduced-form evolution of atmospheric CO_2

$$S_{t+1} = S_{\text{pre-ind}} + \sum_{\ell=1}^{\infty} (1-\delta_\ell)\left(E^f_{t+1-\ell} + E^x_{t+1-\ell}\right)$$

$$(1-\delta_\ell) = a_0 + \sum_{i=1}^{3} (a_i e^{-\ell/b_i})$$

  - $S_{\text{pre-ind}} = 2{,}200$ $GtCO_2$ is carbon stock in the preindustrial era
  - $E^f_t = \int_S \int_0^1 e_t^{f,\omega}(v) H(v) d\omega dv$ are endogenous CO_2 from fuel combustion
  - E^x_t are exogenous CO_2 emissions from forestry (RCP 8.5)
  - $(1-\delta_\ell)$ is share of CO_2 emissions remaining in atmosphere ℓ periods ahead
    - ★ $a_0 = 0.2173, a_1 = 0.2240, a_2 = 0.2824, a_3 = 0.2763,$ $b_1 = 394.4, b_2 = 36.54, b_3 = 4.304$ (IPCC, 2013)

Model: Forcing and Temperature

- Mapping to radiative forcing F_{t+1}

$$F_{t+1} = \varphi \log(S_{t+1}/S_{\text{pre-ind}}) + F^x_{t+1}$$

  - $\varphi = 5.35$ is the forcing sensitivity (IPCC, 2013)
  - F^x_{t+1} is radiative forcing from non-CO_2 GHG (RCP 8.5)

- Reduced-form evolution of global temperature T_{t+1} back

$$T_{t+1} = T_{\text{pre-ind}} + \sum_{\ell=0}^{\infty} \varrho_\ell F_{t+1-\ell}, \quad \varrho_\ell = \sum_{j=1}^{2} \frac{c_j}{d_j} e^{-\ell/d_j}$$

  - $T_{\text{pre-ind}} = 8.1^\circ$C is global temperature in preindustrial era
  - ϱ_ℓ is temperature response to an increase in radiative force ℓ periods ahead
    - $c_1 = 0.631, c_2 = 0.429, d_1 = 8.4, d_2 = 4.095$ (IPCC, 2013)

Estimation: Summary

4. Preferences: $\sum_t \beta^t u_t(r), \quad u_t(r) = \left(1+\Lambda_t^b(r)\right)\bar{b}_{t-1}(r)L_t(r)^{-\lambda}\left[\int_0^1 c_t^\omega(r)^{\rho} d\omega\right]^{1/\rho}, \quad u_0(r)=e^{HDI_0(r)^3/\psi}$	
$\beta = 0.965$	Discount factor
$\rho = 0.75$	Elasticity of substitution of 4 (Bernard et al., 2003)
$\lambda = 0.32$	Relation between amenities and population
$\Omega = 0.5$	Elasticity of migration flows wrt income (Monte et al., 2018)
$\psi = 0.05$	Relation between utility and HDI (Kummu et al., 2018)
5. Technology: $q_t^\omega(r) = \phi_t^\omega(r)^{\gamma_1} z_t^\omega(r)\left(L_t^\omega(r)^\chi e_t^\omega(r)^{1-\chi}\right)^{\mu}, \quad F_{r,t}^\omega(z) = e^{a_t^\omega(r)z^{-\theta}}, \quad a_t^\omega(r) = \bar{a}_t(r)L_t(r)^{\alpha}$	
$\alpha = 0.06$	Static elasticity of productivity to density (Carlino et al., 2007)
$\theta = 6.5$	Trade elasticity (Eaton and Kortum, 2007; Simonovskova and Waugh, 2014)
$\mu = 0.8$	Non-land share in production (Greenwood et al., 1997; Desmet and Rappaport, 2017)
$\gamma_1 = 0.319$	Relation between population distribution and growth
6. Productivity evolution: $\bar{a}_t(r) = (1+\Lambda_t^a(r))\left(\phi_{t-1}(r)^{\theta\gamma_1}\left[\mathcal{D}\int \bar{a}_{t-1}(v)ds\right]^{1-\gamma_2}\bar{a}_{t-1}(r)^{\gamma_2}\right), \quad L^\phi = \nu\phi^\xi$	
$\gamma_2 = 0.993$	Relation between population distribution and growth
$\xi = 125$	Desmet and Rossi-Hansberg (2015)
$\nu = 0.15$	Initial growth rate of real GDP of 1.75%
7. Trade costs	
$\varsigma(\cdot,\cdot)$	Allen and Arkolakis (2014) and Fast Marching Algorithm
8. Migration costs	
$m_2(\cdot)$	Match population distribution in 2005

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Estimation: Energy Productivities

- Compute initial energy productivities $\zeta_0^f(r), \zeta_0^c(r)$
  - First Order Conditions between labor and CO_2, and labor and clean energy

$$\zeta_0^f(r) = \left(\frac{\mu + \gamma_1/\xi}{\mu(1-\chi)\kappa}\right)\left(\frac{e_0(r)}{L_0(r)}\right)\left(\frac{e_0^f(r)}{e_0(r)}\right)^{\frac{1}{\varepsilon}} f(CumCO2_0)$$

$$\zeta_0^c(r) = \left(\frac{\mu + \gamma_1/\xi}{\mu(1-\chi)(1-\kappa)}\right)\left(\frac{e_0(r)}{L_0(r)}\right)\left(\frac{e_0^c(r)}{e_0(r)}\right)^{\frac{1}{\varepsilon}}$$

  - Construct CO_2 emissions and clean energy at cell level
    - ⋆ Country disaggregation (EDGAR, BP)
    - ⋆ Allocate marine and aviation emissions across countries (IEA)
    - ⋆ Disaggregate within country across cells (EDGAR)

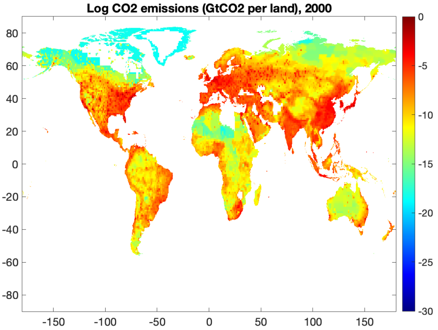
Estimation: Energy

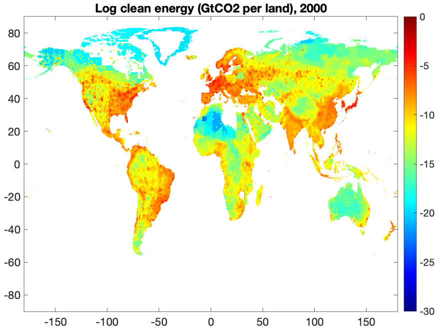
- Set elasticity between fossil fuels and clean energy $\epsilon = 1.6$ back
  - Papageorgiou et al. (2013), Popp (2004)
- Calibrate fossil fuel share, $\kappa = 0.89$, and energy share, $\mu(1-\chi) = 0.03$
  - First Order Conditions between CO_2 and clean energy, and energy and labor

$$\frac{\kappa}{1-\kappa} = \left(\frac{\mathcal{Q}_0^f}{\mathcal{Q}_0^c}\right)\left(\frac{E_0^f}{E_0^c}\right)^{\frac{1}{\epsilon}}, \quad \frac{\mu(1-\chi)}{\mu+\gamma_1/\chi} = \frac{\mathcal{Q}_0 E_0}{L_0}$$

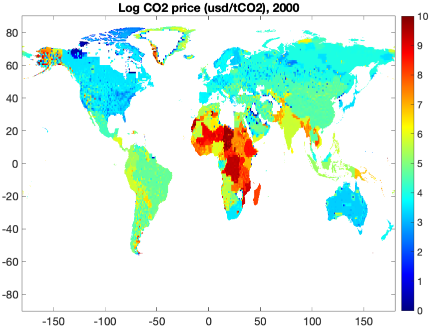
  - Fossil fuel price $\mathcal{Q}_0^f = 73.00$ usd/tCO_2
    - CES composite between oil, nat gas, coal (Golosov et al., 2014)
    - Elasticity of substitution across fossil fuels 1.11 (Stern, 2012)
  - Clean energy price $\mathcal{Q}_0^c = 87.79$ usd/tCO_2
    - Levelized Cost of Energy in electricity (Acemoglu et al., 2019)
    - Lifetime cost in terms of lifetime electricity generation

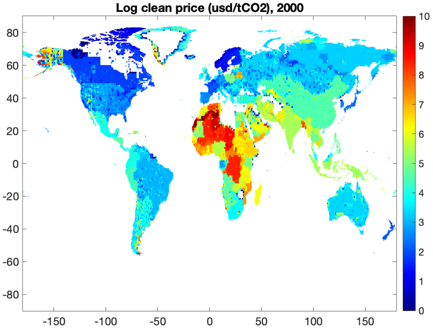
Estimation: Energy





Estimation: Energy





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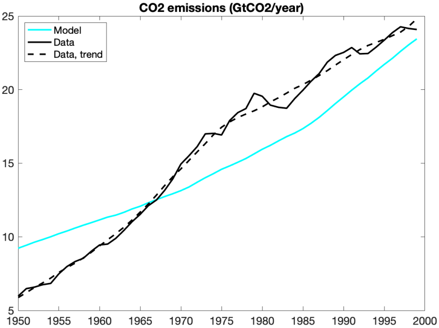
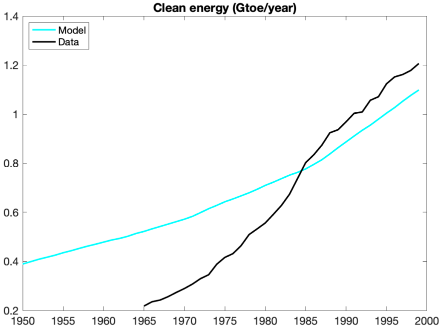
Estimation: Past CO_2 Emissions and Clean Energy





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Estimation: Initial Utility

- Use Human Development Index (HDI) as utility measure
  - Geometric mean of health, education and income
  - Transform HDI into a measure linear in income

$$(HDI_t(r))^3 = \iota_t(r) + \psi_t(r) \log(GNI_t(r))$$

  - Definition of utility by the model

$$\psi \log(u_t^i(r)) = \psi \log\left(b_t(r)\right) + \psi \log(y_t(r))$$

  - Relationship between model-based utility and HDI

$$u_t^i(r) = \exp\left(\frac{(HDI_t(r))^3}{\psi}\right)$$

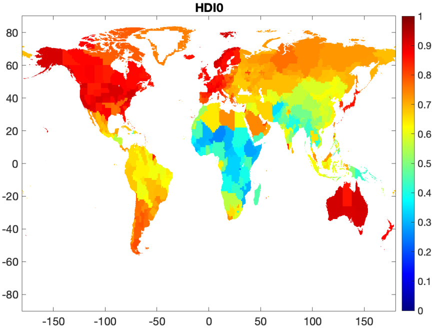
Estimation: Initial Utility

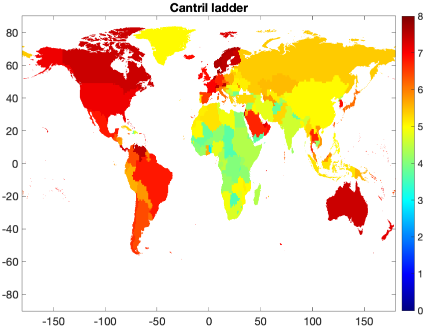
	(1)	(2)	(3)
logrealgdp	0.107***	0.0450***	
	(0.00657)	(0.00813)	
1990×logrealgdp			0.0338***
			(0.00658)
1995×logrealgdp			0.0412***
			(0.00574)
2000×logrealgdp			0.0459***
			(0.00529)
2005×logrealgdp			0.0510***
			(0.00516)
subcountry fe	X	X	X
year fe		X	X
weight pop	X	X	X
N	2,952	2,952	2,952
R^2	0.9822	0.9880	0.9910
RMSE	0.0297	0.0245	0.0211

Standard errors in parentheses, clustered by country

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Estimation: Initial Utility





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Estimation: Natality

- Parametrize natality function $\eta(\cdot)$ back

$$\eta\Big(\log(y_t(r)), T_t(r)\Big) = \eta^y\Big(\log(y_t(r))\Big) + \eta^T\Big(T_t(r), \log(y_t^w)\Big)$$

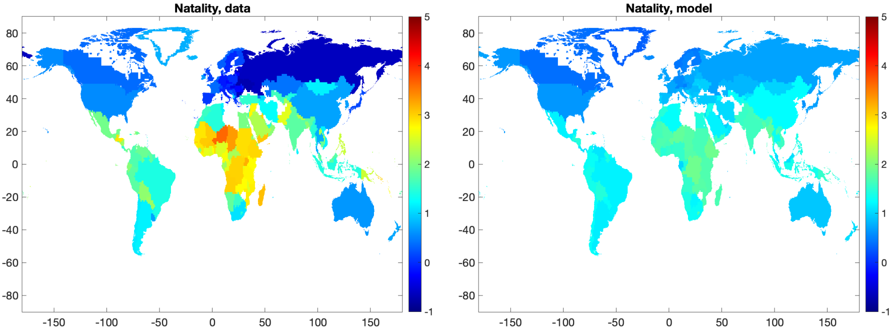
$$\eta^y\Big(\log(y_t(r))\Big) = \mathcal{B}\Big(\log(y_t(r)); b^\ell\Big)\cdot \mathbb{1}\Big(\log(y_t(r)) < b^*\Big) + \mathcal{B}\Big(\log(y_t(r)); b^h\Big)\cdot \mathbb{1}\Big(\log(y_t(r)) \geq b^*\Big)$$

$$\eta^T\Big(T_t(r), \log(y_t^w)\Big) = \frac{\mathcal{B}\Big(T_t(r); b^T\Big)}{1 + \exp\Big(b_w(\log(y_t^w) - \log(y_0(w)))\Big)}$$

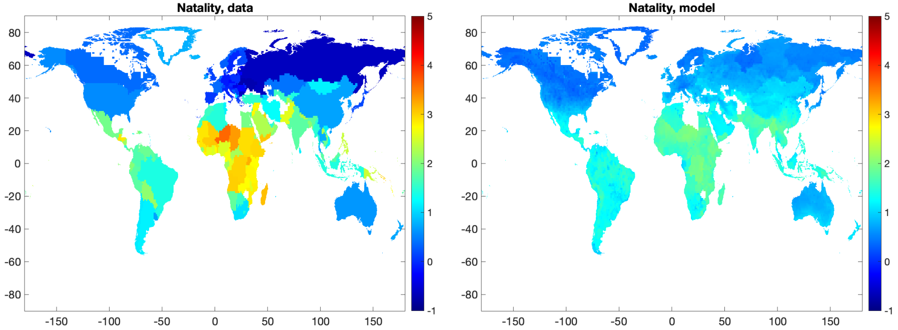
$$\mathcal{B}(x; b) = \big(b_0 + (b_2 - b_0)\exp(-b_1(x - b^*)^2)\big)$$

  - Estimate (b^ℓ, b^h, b^T, b^w) by targeting historical country-level natality rates

Estimation: Natality



Estimation: Natality



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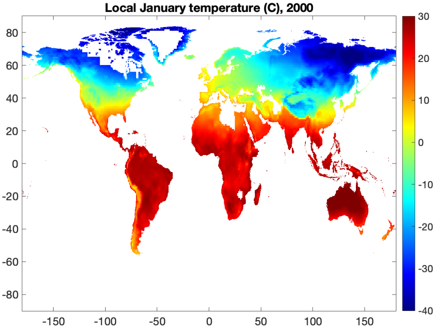
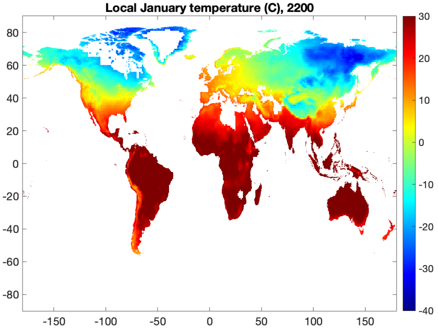
Estimation: Temperature





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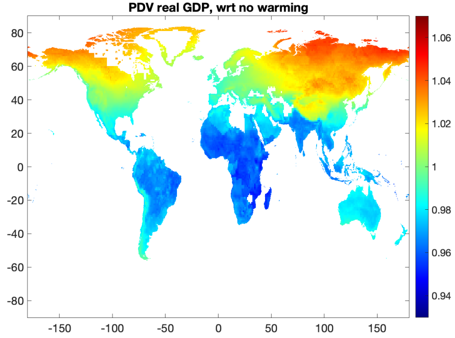
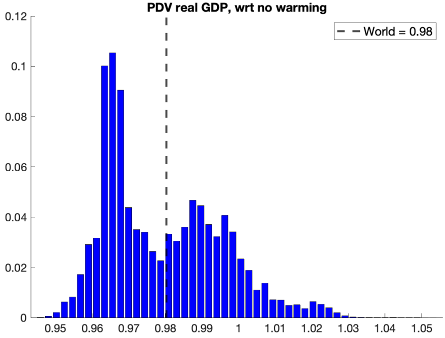
Baseline Scenario: Real GDP Cost of Global Warming





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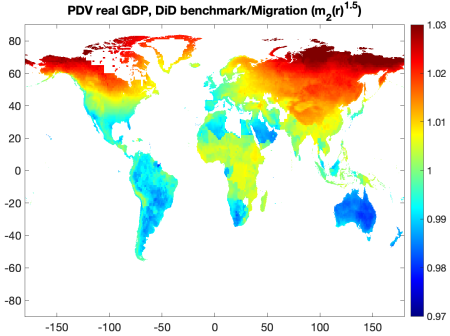
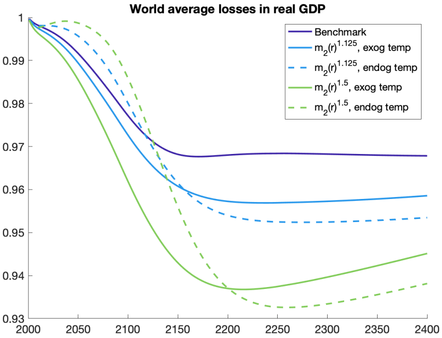
Adaptation: Migration and Real GDP





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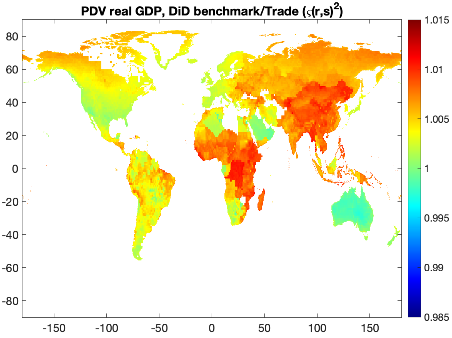
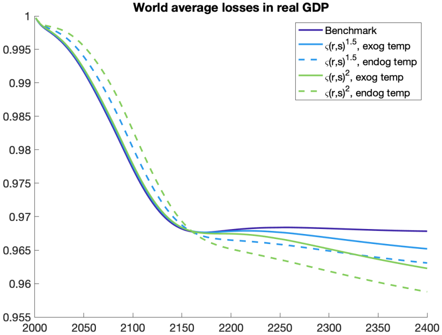
Adaptation: Trade and Real GDP





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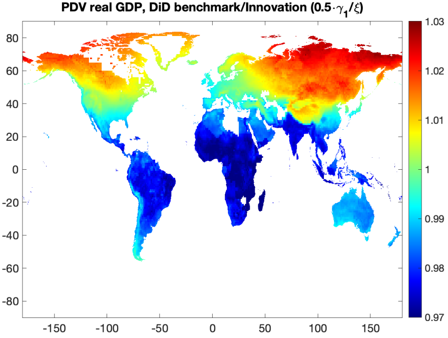
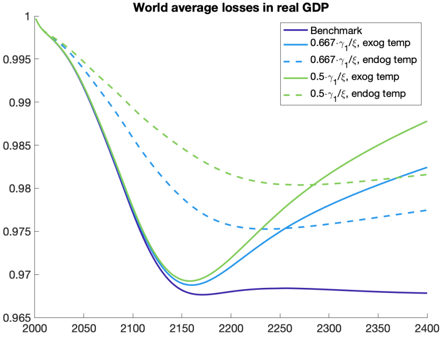
Adaptation: Innovation and Real GDP





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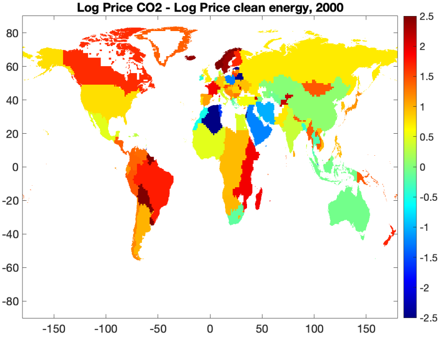
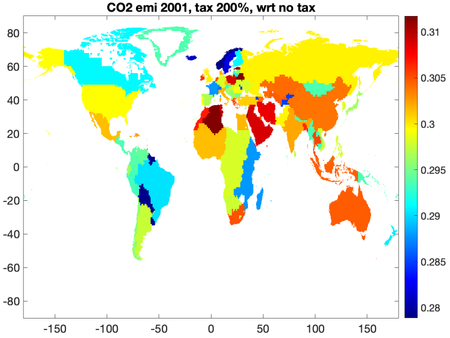
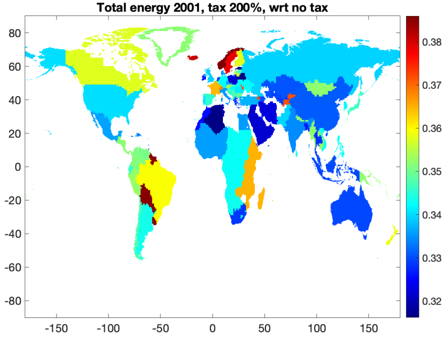
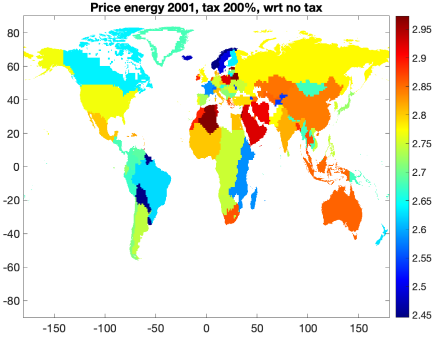
Carbon Taxes





Carbon Taxes





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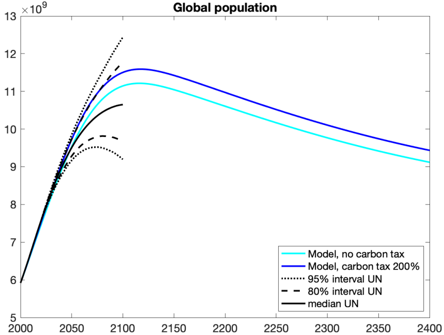
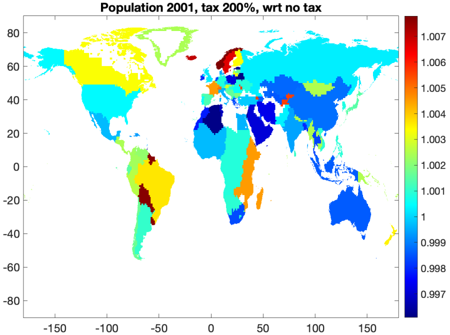
Carbon Taxes





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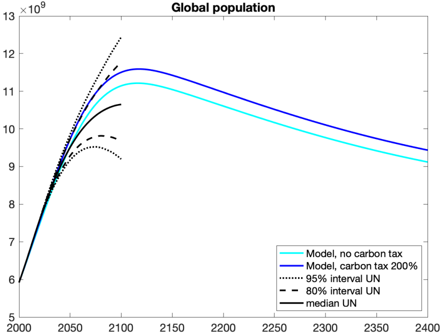

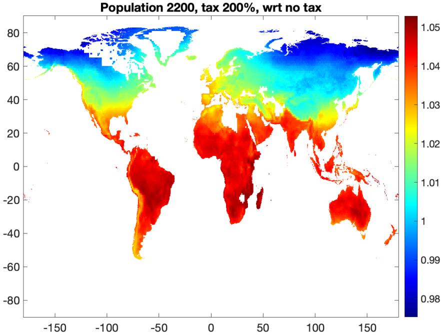

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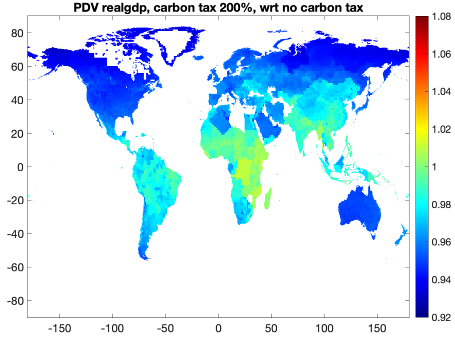
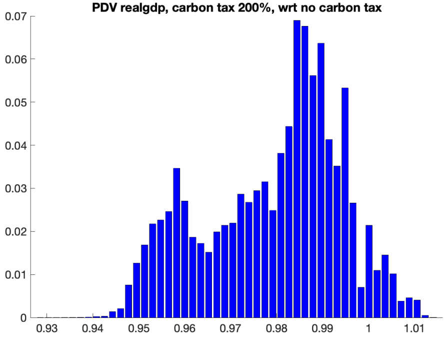
Carbon Taxes: Local Real GDP





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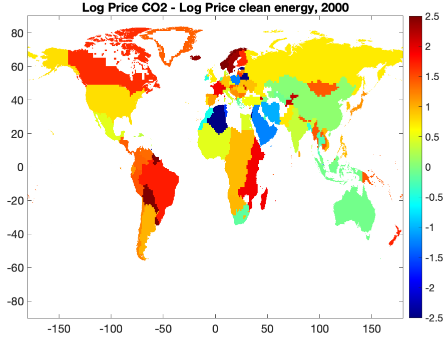
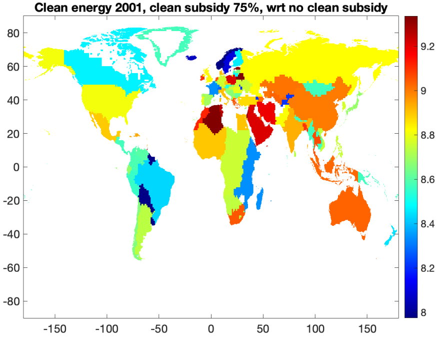
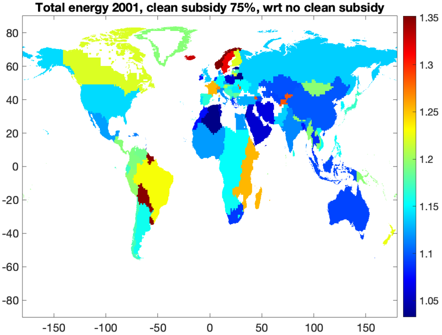
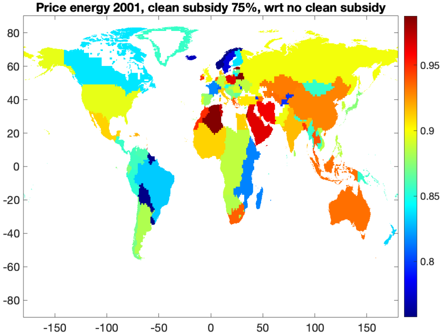
Clean Energy Subsidies





Clean Energy Subsidies





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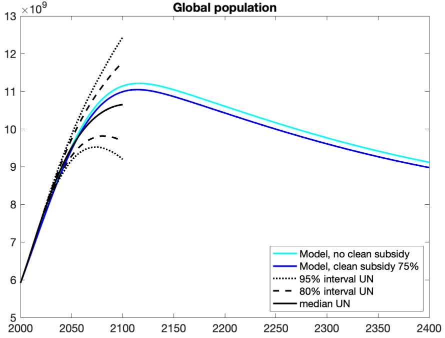
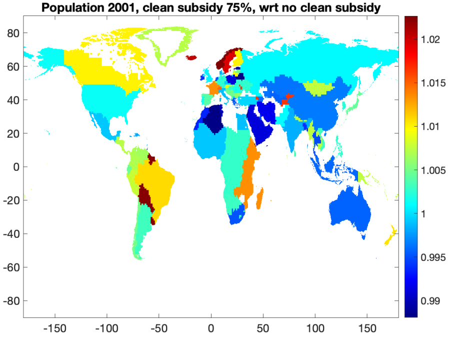
Clean Energy Subsidies





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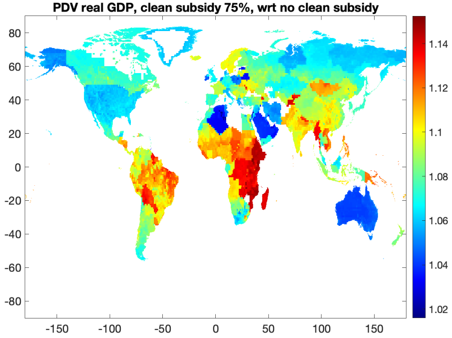
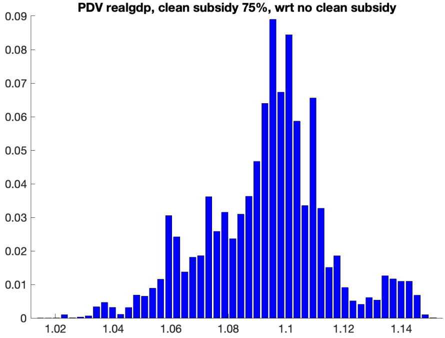
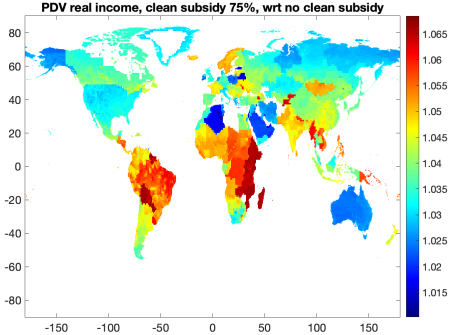
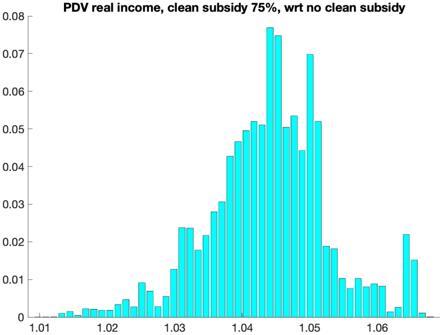
Clean Energy Subsidies: Local Real GDP





Clean Energy Subsidies: Local Real Income





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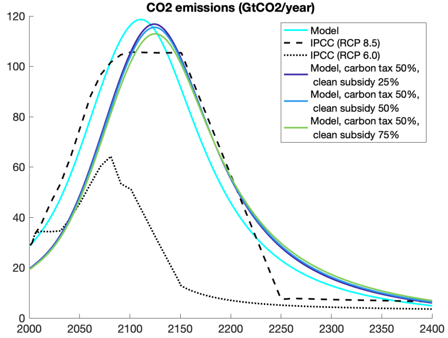
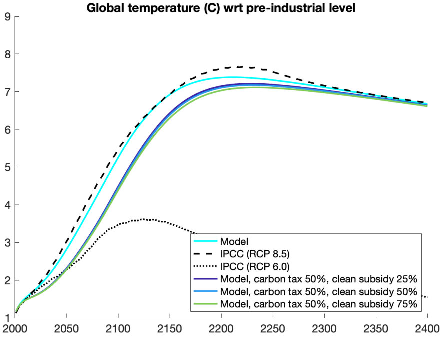
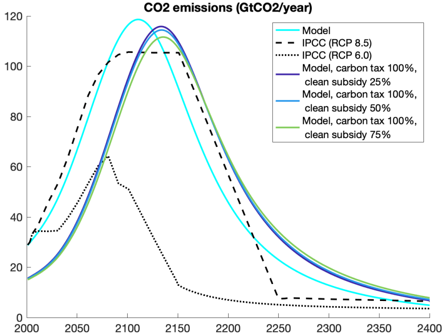
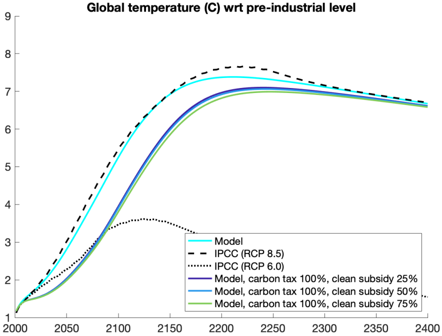
Clean Energy Subsidies



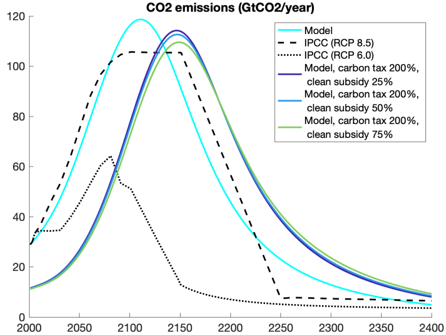


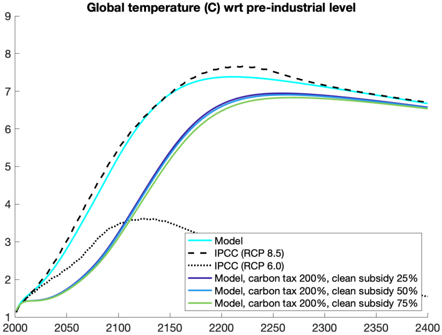
Clean Energy Subsidies





Clean Energy Subsidies





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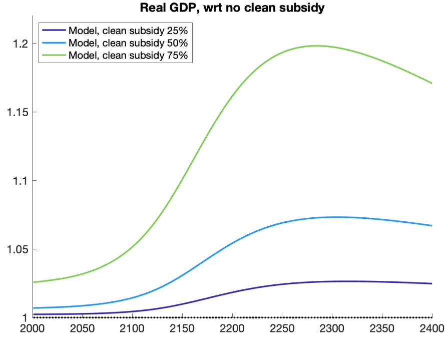
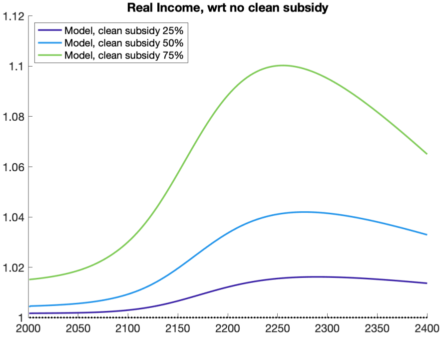
Clean Energy Subsidies: Dynamic Effects





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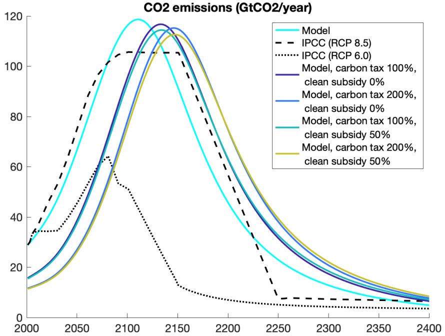
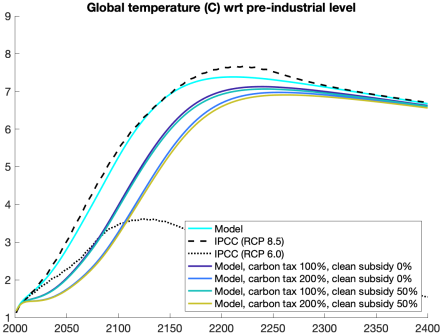
Carbon Taxes and Clean Energy Subsidies





Carbon Taxes and Clean Energy Subsidies: Dynamic Effects