# Geography, uncertainty, and the cost of climate change

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# Spatial IAMs predict small welfare losses from climate change

Estimates of welfare loss around 5-7%, SCC numbers around $5.

Krusell and Smith (2022), Cruz and Rossi-Hansberg (2023)

Major criticism: failing to account for uncertainty!

Pindyck (2013), Wagner and Weitzman (2015)

'Tail' risk large: $> 6^\circ$ warming by 2100 potentially as high as $\sim 10\%$

Weitzman (2009), Weitzman (2011), Wagner and Weitzman (2015)

Cost of tail events large when welfare loss is convex in temperature

**This paper:** Welfare convexity from damage functions versus adaptation forces, accounting for future climate uncertainty

# This paper propagates uncertainty through a SIAM

We study uncertainty around **equilibrium climate sensitivity (ECS)**

(long-run rise in global temperature if atmospheric carbon stock doubles)

We develop a simple quantitative spatial model

- **New:** aggregation + costly international migration – no global spatial equilibrium
- Local damage functions, adaptation through trade and migration

We ask, how do adaptation forces interact with tail risk?

- **New:** Decomposition of second-order welfare impact of climate shock
- Result: adaptive forces concavify the welfare function

We estimate how quantitatively important is climate uncertainty

- Globally: important! Adaptation forces are not strong enough to offset convex damages
- Accounting for uncertainty amplifies spatial inequality, redistributes damages to the global south

# Welfare curvature and climate uncertainty

Quantitative models map changes in climate to welfare,

$$\underbrace{\mathcal{W}}_{\text{welfare}} : \underbrace{c}_{\text{climate} \to \text{damages}} \underbrace{\mapsto}_{\text{general equilibrium}} \mathbb{R}^{+}$$

When $c$ is a realization of a random variable $C$, by Jensen's inequality,

$$\mathbb{E}_C[\mathcal{W}(C)] \neq \mathcal{W}(\mathbb{E}[C])$$

Second order Taylor expansion around $c = 0$

$$\frac{\mathbb{E}_C[\mathcal{W}(C)]}{\mathcal{W}(0)} - \frac{\mathcal{W}(\mathbb{E}[C])}{\mathcal{W}(0)} = \frac{1}{2}\frac{d^2\mathcal{W}}{dc^2}\frac{1}{\mathcal{W}}\bigg|_{c=0} \cdot \underbrace{\text{Var}\,(C)}_{\text{climate uncertainty}} + \mathcal{O}(c^3)$$

When accounting for uncertainty, concavity in the welfare function leads to *overestimated welfare gains and underestimated losses*.

# Model – household preferences

Measure $L_o$ households in country $o$ indexed by $a$

$$\underbrace{\max_{j,d}}_{\text{choose destination country } d \text{ and region } j} \quad \underbrace{\frac{\mathcal{A}_d}{\mu_{od}}}_{\text{migration cost adjusted destination country amenity}} \times \underbrace{A_j(c)\frac{w_j}{\mathcal{P}_d}}_{\text{amenity-adjusted regional real wage}} \times \underbrace{\epsilon^a_{j,d}}_{\text{idiosyncratic preference shock}}$$

- Pay *bilateral* iceberg migration costs $\mu_{od}$
- Local amenities $A_j(c)$ depend on local climate $c$
- Preference shock is *nested Fréchet*,

$$\epsilon \sim \exp\left(-\left(\sum_d\left(\sum_{j\in d} x_j^\eta\right)^{\theta/\eta}\right)^{1/\theta}\right)$$

$\eta$ substitution elasticity over $j$ within $d$; $\theta$: substitution elasticity over $d$

# Model – production

Country $o$ sells aggregate good for price $P_o$ in world markets. Tech:

$$Y_o = \mathcal{Z}_o \left( \sum_j x_j^{\frac{\rho-1}{\rho}} \right)^{\frac{\rho}{\rho-1}}$$

Regions within $o$ produce $y_j$, taking prices $p_j$ as given,

$$y_j = \underbrace{Z_j(c)}_{\substack{\text{local productivity} \\ \text{function of local climate } c}} \underbrace{L_j}_{\text{labor}},$$

Wages are marginal products, $w_j = p_j Z_j$.

Goods are internationally traded with *iceberg trade costs* $\tau_{od}$,

$$\mathcal{P}_d = \left( \sum_o \tau_{od}^{1-\sigma} P_o^{1-\sigma} \right)^{\frac{1}{1-\sigma}}$$

$\sigma$: elasticity of substitution across countries' goods

# Model – goods market and equilibrium

**(Steady state) Eq'm** Given a vector of climate realizations $\{c_j\} \mapsto \{A_j(c), Z_j(c)\}$, for all $d$, eq'm is a set of prices $\{p_j, P_o\}$, wages $\{w_j\}$, migration flows and population distributions $\{L_{od}, L_o, L_j\}$ such that,

1. agents optimally pick their destinations,
2. the labor market clears,
$$L_d = \sum_o L_{od} = \sum_{j \in d} L_j$$
3. the within-country goods market clears $y_j = \left(\frac{p_j}{P_o}\right)^{1-\rho} Y_o$,
4. and the int'l goods market clears $Y_o = \sum_d \left(\frac{\tau_{od} P_o}{\mathcal{P}_d}\right) Y_d$

# Model – aggregation

Destination utility at the country level is,

$$V_d = \mathcal{A}_d \frac{W_d}{\mathcal{P}_d}$$

Welfare living in $o$,

$$\mathcal{W}_o = \left( \sum_d \mu_{od}^{-\theta} V_d^{\theta} \right)^{1/\theta}$$

*Amenity-adjusted expected wages* $W_o$,

$$W_o = P_o \times \underbrace{\left( \sum_{j \in o} (A_j Z_j^{1-1/\rho})^{\frac{\eta\rho}{\rho+\eta}} \right)^{\frac{\rho+\eta}{\rho\eta}}}_{\equiv \tilde{A}_o} \times \underbrace{\left( \sum_{j \in o} \left( \frac{(A_j Z_j^{1-1/\rho})^{\frac{\eta\rho}{\rho+\eta}}}{\sum_{j' \in o} (A_{j'} Z_{j'}^{1-1/\rho})^{\frac{\eta\rho}{\rho+\eta}}} \times Z_j \right) \right)^{\frac{1}{\rho-1}} \mathcal{Z}_o^{1/\rho}}_{\equiv \tilde{Z}_o}$$

$\tilde{A}_o$: aggregate amenity, $\tilde{Z}_o$: aggregate productivity
Aggregates *account for adaptation through internal spatial sorting*

# International migration and trade flows

Migration flows

$$L_{od} = \frac{(V_d/\mu_{od})^\theta}{\sum_e (V_d/\mu_{oe})^\theta} L_o$$

Trade flows,

$$X_{od} = \left(\frac{\tau_{od} P_o}{\mathcal{P}_d}\right) Y_d$$

In aggregate, model is Armington trade with costly migration!

Aggregate amenities and productivities...

- depend on the spatial distribution of $\{A_j\}$ and $\{Z_j\}$ *within nations*
- and account for household location choice

# Convexity of a nation's welfare = local curvature + trade and migration adaptation

Recall, Jensen's correction depends on $\frac{d^2 \log \mathcal{W}_o}{dc^2}$. Through the structure of the model,

$$\frac{d^2 \log \mathcal{W}_o}{dc^2} = \underbrace{\frac{d^2 \log \tilde{A}\tilde{Z}}{dc^2}}_{\text{local curvature, accounting for adaptation}} + \underbrace{(\sigma - 1)\text{Var}_{T_{do}}\left(\frac{d \log P_d}{dc}\right)}_{\text{adaptation thru int'l trade}} + \underbrace{\theta \text{Var}_{M_{od}}\left(\frac{d \log(V_d / V_o)}{dc}\right)}_{\text{adaptation through emmigration}}$$

$$+ \underbrace{\sum_d M_{od} \frac{d^2 \log(V_d / V_o)}{dc^2} - \sum_d T_{do} \frac{d^2 \log P_d}{dc^2}}_{\text{second order GE price effects}}$$

National internal geography matters:

- local adaptation captured in curvature of aggregate amenities and productivities

International geography matters:

- Adaptation through *int'l* trade and migration depends on spatial dispersion of international shocks, *weighted by the trade and migration matrices*

# Gravity regressions recover $\mu_{od}$, $\tau_{od}$

**New:** $\{\mu\}$ from int'l migration gravity,

$$\log L_{od} = -\theta \log \mu_{od} + \theta \log V_d - \theta \log \mathcal{W}_o + cons$$

Problems: Flows $L_{od}$ backed out from demographic acc'ting + World Bank migrant stock data (Abel and Cohen, 2019) measured with error.

*Many zeros* in international migration matrix.

Solution is smoothing: use Poisson regression to project $\mu_{od}$ onto bilateral covariates (Dingel and Tintelnot 2024):

$$Flows_{od} = \xi_i \exp(X_{ij}'\beta)\xi_j u_{ij}, \quad \mathbb{E}[u_{ij} \mid \xi_i, \xi_j, X_{ij}] = 1. \quad \hat{\mu}_{od}^{-\theta} = \exp(X_{ij}'\hat{\beta})$$

Estimate with maximum likelihood.

Standard Armington Gravity for $\tau_{od}$ with PPML estimator.

# Int'l migration gravity looks a lot like trade, but distance-elastic

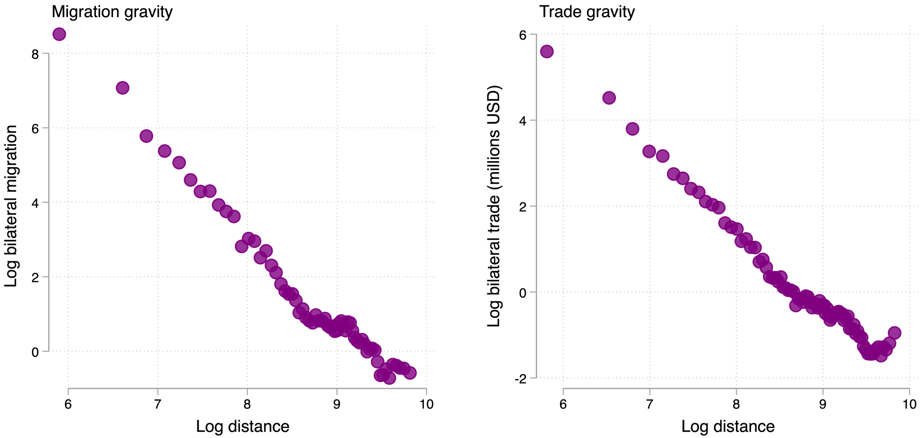


Figure 1: Gravity in migration and trade, distance conditional on other gravity variables

Migration gravity variables: standard gravity variables + border permeability index, visa costs!

# Damage functions

Need to map changes in local climate (temperature, $c$) to changes in amenities and productivities. Steps:

1. Assume a *damage function*,

$$\log A_{jt} = \beta_0 \underbrace{T_{jt} + \beta_1 T_{jt}^2}_{\text{temperature polynomial}} + \underbrace{X_j \Gamma}_{\text{covariates}} + \underbrace{\zeta_o + \zeta_t}_{\text{fixed effects}} + e_{jt}$$

2. Recover bell-curve shaped damage function,

$$A_j(T_j) = \bar{A}_j \exp\left(-\frac{1}{2}(T_j - \hat{\mu})^2 / \hat{\xi}\right)$$

where,

$$\hat{\mu} = -\hat{\beta}_0/(2\hat{\beta}_1), \hat{\xi} = -1/(2\hat{\beta}_1)$$

# Estimated damage functions

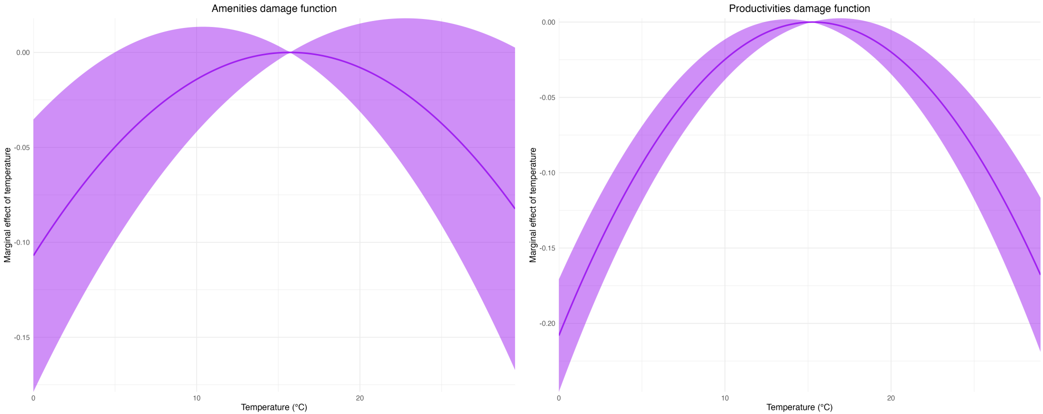


Figure 2: Left: amenities damage function. Right: productivities damage function

# Estimating downscaling: map global $\rightarrow$ local temperature

Again, similar approach to Cruz and Rossi-Hansberg (2023):

Downscaling linear in global temp:

$$\underbrace{t_{it}}_{\text{local temp}} = \underbrace{g_i}_{\text{downscaling}} \cdot \underbrace{T_t}_{\text{global temp}} + \alpha_i + u_{it}$$

- Data: Berkeley 'BEST' temperature data – annual coverage 1894-today
- Cell-specific correlations, no projection

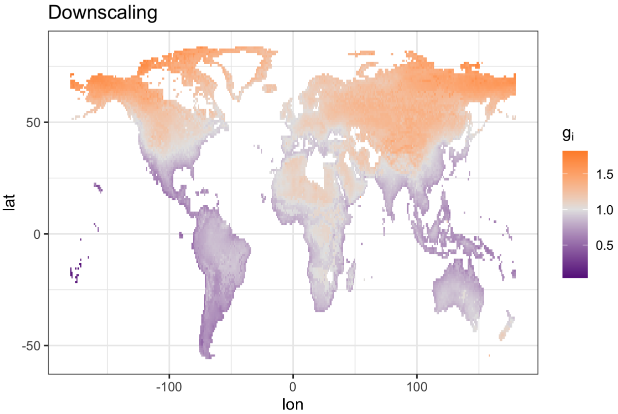


Figure 3: Estimated downscaling parameters $\hat{g}_i$.

# Welfare exercise – 2$\times$ stock of carbon today, check in 100 years on

Uncertainty from ECS scenario uncertainty

- Following Schwarzwald and Lenssen (2022), working on internal variability (here $\approx$ econometric uncertainty for damage functions, downscaling)
- No parameter ambiguity (unknown $\theta, \eta, \sigma$)
- Open to ideas!

We focus on different climate models' assessment of what doubling the stock of atmospheric carbon today would do to global temperatures in the long-run (ECS).

We take the distribution of ECS estimates as given, and evaluate global welfare for each potential effect.

# Global welfare is *concave*

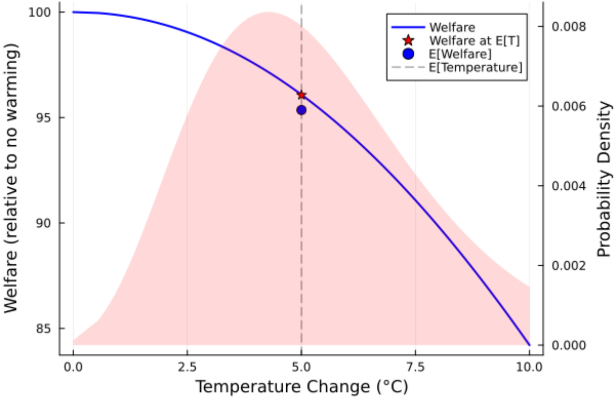


Figure 4: Expected welfare loss of 4.64% at a global level

Welfare loss is 18.1% higher (0.72pp) accounting for uncertainty. Globally,

$$\frac{\mathbb{E}_C[\mathcal{W}(C)]}{W(0)} - \frac{\mathcal{W}(\mathbb{E}_C[C])}{W(0)} < 0$$

# Welfare functions across countries

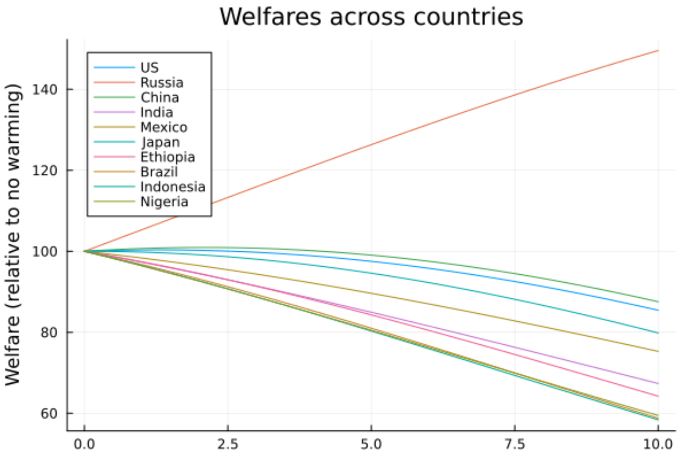


Figure 5

Countries vary in terms of welfare damages *as well as* curvature in welfare function

# Global distribution of damages accounting for uncertainty

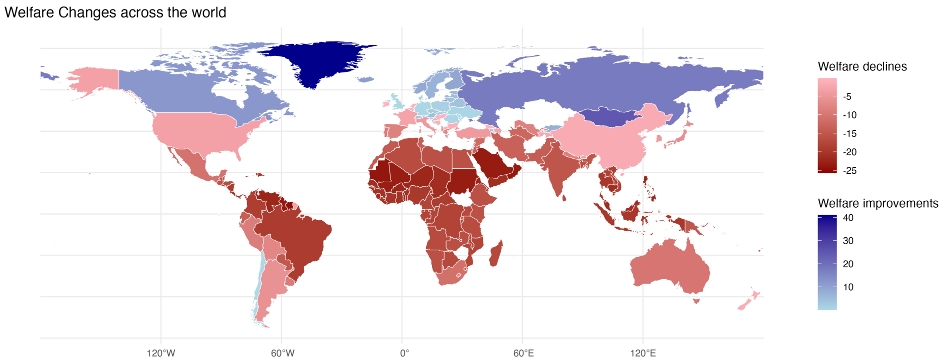


Figure 6: Distribution of $\frac{\mathbb{E}[\mathcal{W}_o(C)]}{\mathcal{W}_o(0)}$

# The geography of climate uncertainty – mapping the Jensen's correction term

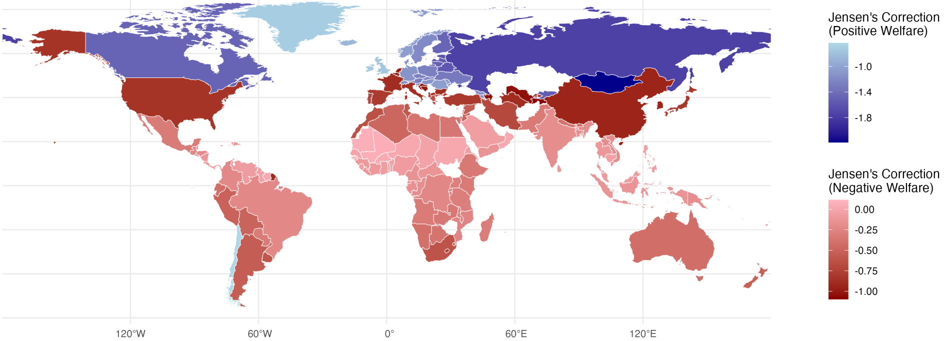


Figure 7: Numerical $\frac{\mathbb{E}[\mathcal{W}_O(C)]}{\mathcal{W}_O(0)} - \frac{\mathcal{W}_O(\mathbb{E}[C])}{\mathcal{W}_O(0)}$

Accounting for uncertainty *redistributes damages* to the global south

# Internal temp variance and welfare

Countries with greater variance in temperature distribution across regions within their borders have a greater ability to adapt via internal trade and migration:

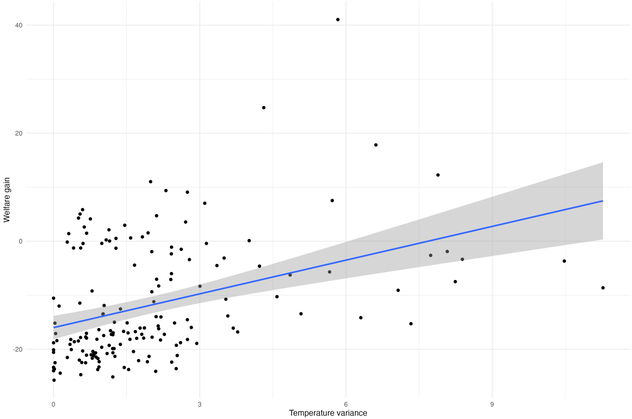


Figure 8: Change in welfare vs variance in temperature

# Conclusion and next steps

When accounting for ‘tail risk’ by integrating over the full future potential temperature distribution...

- Welfare loss depends on the curvature of the welfare function
- Even if damage functions are convex in losses...
- ...local and international adaptation through trade and migration and attenuate damages
- depends critically on geography: whether there is enough (trade and migration weighted) variance in local climate shocks to allow countries to adapt!

Empirically, adaptation forces are not enough to ‘undo’ welfare convexity from estimated damages.

- This matters empirically: accounting for uncertainty, *spatial inequality* in the welfare effects of climate change are amplified!

**Next steps:** accounting for the different mechanisms...

...and accounting for geography: is it ‘bad luck’ that the spatial distribution of the climate shock amplifies welfare losses?