Economic Impacts of Climate Uncertainty

(*very preliminary*)

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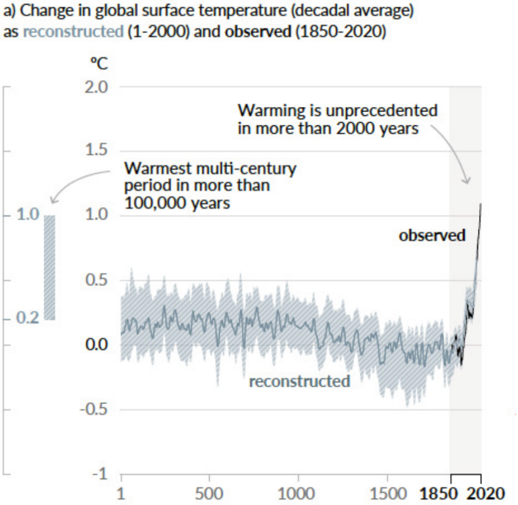
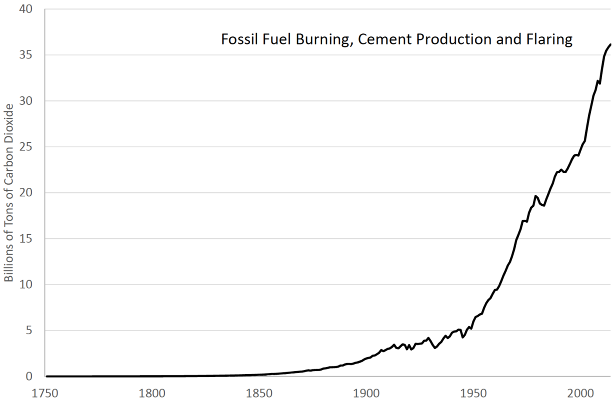
Global warming is real according to the scientific community



Resource: 6th IPCC Report

Why is it happening? Greenhouse gas (CO2) is most likely to be a reason!

Global CO2 Emissions: 1751-2014



Resource: CDIAC, ORNL (2017)

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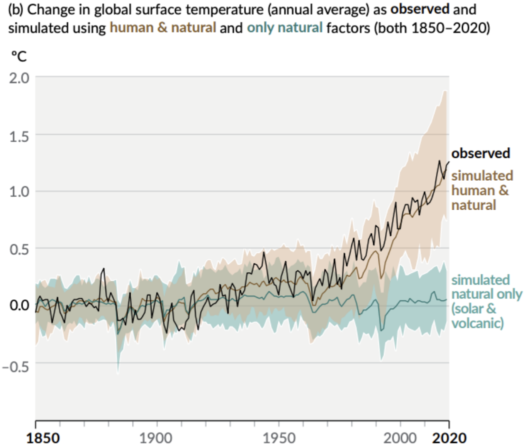


Resource: 6th IPCC Report

So what? Why should we (economists) care about global temperature rise?

- ✓ Reduction in TFP due to climate change as well as extreme weather effects
  - Heat waves, heavy precipitation, severe drought, crop failures and etc, e.g., Mendelsohn et al. (1994), Burke et al. (2015), Tol (2021)
- ✓ Utility and health loss due to environmental disruptions, e.g., Baylis (2015) and Albouy et al. (2016)
- ✓ Possibility of civilization ending catastrophe due to tipping point, e.g., Dietz et al. (2021)
- ✓ Possibility of social unrest due to migrations and (trade) wars triggered by climate change, e.g., Missiran and Schlenker (2017) and Cruz and Rossi-Hansberg (2020)
- ✓ Financial risks during transition towards a green economy, e.g., FSB report (2020)

The problem is all these costs are externalities!

✓ Not internalized by private market system (ultimate market failures)

✓ Market-based policy instruments implemented to correct for these externalities

- Cap-and-trade system (quantity control): EU emissions trading system (since 2005), Korea emissions trading scheme (since 2015), and etc.
- Carbon tax: Canada, California, Northern European countries, and etc.

✓ Optimal social externality costs of carbon(OSCC) emissions are essential

✓ How to correctly estimate them?⇒ Macro problem!

- OSCC≡ Pigouvian tax≡ marginal damages evaluated at ***optimal allocation***
- Structured models are required

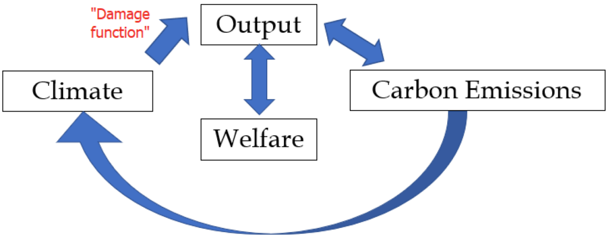
Integrated Assessment Models (IAMs)

✓ Nordhaus' (2018 Nobel Laureate) first dynamic integrated model of climate and the economy (DICE): Nordhaus (1992)

- Can first perform internally consistent cost-benefit analysis!
- Can first solve dynamically optimal social cost of carbon!

✓ Rejected from all top 5 econ journals but published in *Science*

✓ Addition of *damage function* was crucial!



DICE in a nutshell

- ✓ Output: Climate impacts summarized by damage function $D(T_t)$

$$Y_t = (1 - D(T_t))A_t K_t^{\alpha} L_t^{1-\alpha},$$

where $T_t \approx$ mean global atmospheric surface temperature change

- ✓ Carbon emissions: σ_t is emissions intensity

$$E_t = (1 - \mu_t)\sigma_t Y_t$$

where $\mu_t \in [0, 1]$ refers to the abatement rate

- ✓ Climate proxied by T_t

$$T_t = \bar{T} + \eta \log_2 \left(E_t / \bar{E}\right)$$

where $\bar{T}$ and $\bar{E}$ represents baseline temp change and carbon emission respectively

Standard estimation methods for $D(T_t)$

- ✓ **Ricardian Cross-Sectional Approach**: Mendelsohn, Nordhaus, and Shaw (1994) and etc.

$$y_i = \mathbf{Z}_i\beta + \mathbf{X_i}\tau + \varepsilon_\mathbf{i},$$

where $\mathbf{Z_i}$ is a vector of average climate variables in region and/or sector i

- ✓ **Panel Approach**: Dell et al. (2012) and Kalkhul and Wenz (2020)

$$y_{i,t} = \alpha_i + \mathbf{Z}_{i,t}\beta + \mathbf{X_{i,t}}\tau + \varepsilon_{\mathbf{i,t}},$$

where α_i is a time-invariant individual effect

- ✓ **Long-Difference Approach**: Burke and Emerick (2016)

$$\Delta y_i = \Delta\mathbf{Z}_i\beta + \mathbf{X_i}\tau + \varepsilon_\mathbf{i},$$

where Δy_i and $\Delta\mathbf{Z_i}$ denotes changes in y_i and climate variables respectively over a long period (several decades)

What's wrong with the existing methods? Auffhammer (2018)

- ✓ Omitted variables bias from the cross-sectional approach:
  - somewhat mitigated by panel approach due to fixed effects
- ✓ Climate adaptation not fully taken into account:
  - year-to-year variations only capture short-run adaptation to weather fluctuations
- ✓ Long-difference approach still flawed:
  - past historical relationship may not be stable in the future (Lucas critique)
- ✓ Climate change also means changes in higher moments of weather distribution:
  - **Climate uncertainty** or extreme weather effects recently got a lot of attention
  - Alessandri and Mumtaz (2021)

What we do and contribute

Two folds:

1. Accounting for long-term climate adaptation ⇒ 'Climate' rather than 'Weather' effects
2. Accounting for 'Climate uncertainty' effects, i.e., effects of changes in second moments

How?: ⇒ Stochastic Frontier Model e.g., Tol (2021)

- ✓ Benefit 1: Allows to incorporate (random) inefficiency into estimation of production functions
- ✓ Benefit 2: Can separately identify the effects of climate and weather
- ✓ Benefit 3: Not required to have additional variables to identify the distribution of inefficiency

Data

- ✓ Macro economics data: output, capital, population, labor
  - Penn World Table (PWT), PWT 10.0 (Feenstra et al., 2015)
- ✓ Global weather data: air temperature and precipitation only
  - *Terrestrial air temperature and precipitation: 1900-2017 time series, (V 5.01)* (Matsuura and Willmott, 2015)
  - Gridded data with a resolution 0.5 $\times$ 0.5 degrees
  - Aggregated into the country-year level, weighting them by population density in the year 2000
  - Population data from Version 4 of the *Gridded Population of the World*

Summary statistics

Variable	Mean	Std.	Min.	Max.	Obs.	Num. of ID
rGDP	10.606	2.112	4.327	16.658	8,554	162
Employment	1.134	1.733	-5.422	6.683	7,742	161
Capital	11.140	2.312	4.277	18.055	8,543	162
Mean:						
Temperature	17.643	8.305	-5.326	29.144	12,916	190
Precipitation	1.098	0.813	0	3.727	12,916	190
Standard Deviations:						
Temperature	0.447	0.210	0	1.374	12,915	190
Precipitation	0.125	0.134	0	0.922	12,915	190
Deviation:						
Temperature	0.942	0.713	0.000	5.427	12,376	182
Precipitation	0.829	0.688	0.000	13.040	12,376	182

Note: All variables are log-transformed. Macro. variables are in millions and 2011 USD. The units of temperature and precipitation are Celsius and meter, respectively. 'rGDP' indicates real GDP at constant 2011 national prices. The timespan starts from 1950 and unbalanced. Mean and standard deviation values are calculated as 30-year rolling window from period $t-30$ to period $t-1$ by using annual temperature and precipitation data. Deviation values are the normalized values of annual temperature and precipitation, respectively.

Model for estimation

Based on a CD production function

$$Y_{i,t} = A_{i,t} K_{i,t}^{\beta} L_{i,t}^{1-\beta} \;\Rightarrow\; \log(y_i, t) = A_{i,t} + \beta \log(k_{i,t})$$

Assumption: $A_{i,t} \equiv$ a function of $\bar{T}_{i,t}$, $\bar{R}_{i,t}$, $\sigma_{T,i,t}$, and $\sigma_{R,i,t}$

$\bar{T}_{i,t} \equiv$ the average temperature in the 30 years preceding year t

$\bar{R}_{i,t} \equiv$ the average precipitation in the 30 years preceding year t

$\sigma_{T,i,t} \equiv$ the STDV of temperatures in the 30 years preceding year t

$\sigma_{R,i,t} \equiv$ the STDV of precipitation in the 30 years preceding year t

Model for estimation

Hence, the frontier equation is given by

$$\log(y_{i,t}) = \beta_1 \log(k_{i,t}) + f(\bar{T}_{i,t}, \bar{R}_{i,t}, \sigma_{T,i,t}, \sigma_{R,i,t}) + \mu_i + t + v_{i,t} - u_{i,t}, \tag{1}$$

where f is known up to a finite-dimensional parameter, and $v_{i,t} \sim N(0, \sigma_v^2)$

The inefficiency equation

$$u_{i,t} = \exp(z_{i,t}^{'}\delta) \cdot u_i^*, \tag{2}$$

where $u_i^* \sim N^+(0, \sigma_u^2)$, and z_{it} contains $\frac{T_{i,t} - \bar{T}_{i,t}}{\tau_{i,t}}$ and $\frac{R_{i,t} - \bar{R}_{i,t}}{\rho_{i,t}}$

Estimation procedure for eq.(1) and eq.(2)

We adopt the estimation approach proposed by Wang and Ho (2010)

- ✓ Maximum likelihood estimation after applying the within or first-differencing transformation
- ✓ Can allow for the individual fixed effects without the incidental parameter problem
- ✓ Either large N or large T

Baseline results 1

Linear Model

	rGDP	rGDPo	rGDPe
FRONTIER			
Employment	0.408***	0.210***	0.210***
	(0.0126)	(0.0125)	(0.0126)
Capital	0.518***	0.655***	0.656***
	(0.0053)	(0.0052)	(0.0053)
Mean:			
Temperature	–0.187***	–0.096***	–0.113***
	(0.0170)	(0.0167)	(0.0169)
Precipitation	0.799***	0.441***	0.444***
	(0.1390)	(0.1370)	(0.1380)
Std.:			
Temperature	–0.085*	0.003	–0.004
	(0.0504)	(0.0500)	(0.0505)
Precipitation	–0.044	0.090	0.084
	(0.1840)	(0.1840)	(0.1860)
H1EQ			
Deviation:			
Temperature	–1.924	0.002	0.230
	(1.9020)	(0.0169)	(0.3420)
Precipitation	–0.725	–0.000	–0.011
	(0.7480)	(0.0023)	(0.0633)
CONSTANT			
vsigmas	–2.822***	–2.853***	–2.831***
	(0.0164)	(0.0165)	(0.0164)
usigmas	–6.634***	5.441	–5.314
	(1.1670)	(19.830)	(4.211)
Obs.	7,623	7,623	7,623

Note: The numbers in parentheses indicate the standard errors. For robustness check, we include ‘rGDPo’ and ‘rGDPe’ which are real GDP at chained PPPs in 2011 USD for output- and expenditure-side, respectively. *, **, and *** denote significance at 10%, 5%, and 1%, respectively.

Baseline results 2 & 3 (next)

Linear Model with Dummies

	$\ln(y_{i,t})$	$D_{Hot}=1$	$\ln(y_{i,t})$	$D_{Rich}=1$
FRONTIER				
Employment	0.447***		0.411***	
	(0.0130)		(0.0126)	
Capital	0.511***		0.516***	
	(0.0053)		(0.0053)	
Mean:				
Temperature	–0.040	–0.284***	–0.227***	0.133***
	(0.0243)	(0.0319)	(0.0208)	(0.0313)
Precipitation	1.149***	–0.535*	0.871***	–0.421
	(0.2266)	(0.2872)	(0.1623)	(0.3139)
Std.:				
Temperature	0.016	–0.369***	–0.046	–0.190*
	(0.0762)	(0.1040)	(0.0707)	(0.1020)
Precipitation	–0.119	0.171	–1.328***	2.695***
	(0.0003)	(0.3744)	(0.2588)	(0.3888)
H1EQ				
Deviation:				
Temperature	0.121	–1.444	–1.348	1.380
	(0.3040)	(1.6440)	(1.5720)	(1.5750)
Precipitation	–0.385	0.186	–0.493	0.491
	(0.8030)	(0.9730)	(0.5360)	(0.5540)
CONSTANT				
vsigmas	–2.841***		–2.833***	
	(0.0164)		(0.0164)	
usigmas	–6.343***		–5.822***	
	(1.6490)		(1.1290)	
Obs.	7,623		7,623	

Note: $y_{i,t}$ indicates real GDP at constant 2011 national prices. The numbers in parentheses indicate the standard errors. *, **, and *** denote significance at 10%, 5%, and 1%, respectively.

Quadratic Models

	$\ln(y_{i,t})$	$\ln(y_{i,t})$	$D_{Hot}=1$	$\ln(y_{i,t})$	$D_{Rich}=1$
FRONTIER					
Employment	0.448***	0.447***		0.455***	
	(0.0129)	(0.0131)		(0.0130)	
Capital	0.513***	0.513***		0.505***	
	(0.0052)	(0.0053)		(0.0053)	
Mean:					
Temperature	0.203***	0.146***	–0.866***	0.157***	0.077
	(0.0394)	(0.0526)	(0.2190)	(0.0592)	(0.0808)
Temperature^2	–0.012***	–0.0112***	0.0180***	–0.008***	–0.013***
	(0.0010)	(0.0019)	(0.0046)	(0.0013)	(0.0020)
Precipitation	2.048***	3.490***	–2.991***	2.442***	–5.098***
	(0.3180)	(0.4840)	(0.9250)	(0.4060)	(0.8130)
Precipitation^2	–0.411***	–1.260***	1.083***	–0.124	–1.007***
	(0.0711)	(0.1590)	(0.1850)	(0.0827)	(0.1940)
Temp * Prec	0.031**	0.101***	–0.056	–0.0456**	0.407***
	(0.0146)	(0.0292)	(0.0388)	(0.0179)	(0.0354)
Std.:					
Temperature	–0.154***	–0.036	–0.321***	–0.0964	–0.246**
	(0.0507)	(0.0736)	(0.1050)	(0.0708)	(0.1010)
Precipitation	–0.249	–0.405	0.441	–1.234***	3.365***
	(0.1840)	(0.2580)	(0.3770)	(0.2580)	(0.3990)
H1EQ					
Deviation:					
Temperature	–2.259	0.652**	–1.714	–1.295	1.253
	(1.9630)	(0.330)	(4.5280)	(1.6280)	(1.6480)
Precipitation	–0.775	–59.77	59.55	–0.537	0.437
	(0.7790)	(62.710)	(62.840)	(0.5660)	(0.6250)
CONSTANT					
vsigmas	–2.845***	–2.857***		–2.872***	
	(0.0164)	(0.0164)		(0.0164)	
usigmas	–6.557***	–5.686***		–5.921***	
	(1.184)	(1.183)		(1.1850)	
Obs.	7,623			7,623	

Note: $y_{i,t}$ indicates real GDP at constant 2011 national prices. The numbers in parentheses indicate the standard errors. *, **, and *** denote significance at 10%, 5%, and 1%, respectively.

Concluding Remarks

- ✓ A stochastic frontier model
  - climate in the frontier
  - weather shocks as a source of inefficiency
- ✓ Only the climate effect is statistically significant while the weather effect is not
- ✓ Climate change effect:
  - Temperature affects production possibilities negatively in hot or poor countries
  - Rainfalls negatively affects production possibilities in hot countries
- ✓ Climate uncertainty effect:
  - Temperature uncertainty ***negatively*** affects production possibilities in both hot and **rich** countries.

Next steps

✓ Different uncertainty measures

- conditional (*ex-ante*) volatility instead of *realized* volatility
- Panel VAR, e.g., Alessandri and Mumtaz (2021)

✓ Climate uncertainty adjusted optimal social cost of carbon:

- IAM with endogenous abatement rates: Golosov, Hassler, Krusell, and Tsyvinski (2014)
- Abatement efforts determined by future climate uncertainty
- Epstein-Zin preferences: Bansal, Kiku, and Ochoa (2016)

✓ Green monetary policy augmented with climate uncertainty? Papoutsi, Piazzesi, and Schneider (2021)

- Climate uncertainty affects valuation of green bonds? If so, how?
- Welfare effects of green quantitative easing with climate uncertainty?