`EC1340 Topic #5`

Climate damage II

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Outline

Climate Change and Economic Growth: Evidence from the Last Half Century

Dell, Jones, Olken (2008)

This paper estimates the effects of climate change on the GROWTH of gdp, rather than it's level. It's a difficult paper. I'm going to go through it very carefully so that you can read it.

Data:

- 50 years of average annual temperature and rainfall by country.
- Annual gdp data for 136 countries with at least 20 years of data in Penn World Tables.

Notation

$$\begin{aligned}
i, t &\sim \text{country index, time index} \\
Y_{it} &\sim \text{GDP} \\
L_{it} &\sim \text{population} \\
T_{it} &\sim \text{temperature (and rainfall)} \\
g_{it} &\sim \text{growth rate of per capita GDP from } t-1 \text{ to } t \\
A_{it} &\sim \text{`Total Factor Productivity' or `Efficiency'} \\
\Delta x_{it} &\equiv x_{it} - x_{it-1}
\end{aligned}$$

Technical aside

First, we need a trick:

For x small

$$\begin{aligned}\ln(1+x) &\approx \ln(1) + x\frac{d}{dx}\ln(x)|_{x=1} \\ &= \ln(1) + x\frac{1}{1} \\ &= x\end{aligned}$$

Now, note that we can derive g from Y and L

$$
\begin{aligned}
1 + g_{it} &\equiv \frac{\frac{Y_{it}}{L_{it}}}{\frac{Y_{it-1}}{L_{it-1}}} \\
&= \frac{\frac{Y_{it}}{Y_{it-1}}}{\frac{L_{it}}{L_{it-1}}}
\end{aligned}
$$

Using our trick for small logarithms, we have

$$
g_{it} \approx \ln\left(\frac{\frac{Y_{it}}{Y_{it-1}}}{\frac{L_{it}}{L_{it-1}}}\right)
$$

Model I

Suppose the relationship between climate, T and output Y is determined by the following two equations:

$$Y_{it} = e^{\beta T_{it}} A_{it} L_{it} \tag{1}$$

$$\frac{\Delta A_{it}}{A_{it-1}} = g_i + \gamma T_{it} \tag{2}$$

- γ determines relationship between climate and growth.
- β measures relationship between climate and level of output.
- g_i is time invariant growth rate for country i.
- Eqn (1) defines A, it's country specific productivity.
- Note typo in time subscript for A_{it-1} in paper.

We want to use this model to help us to understand a regression of g on T.

- Take logs of (1)

$$\begin{aligned} \ln Y_{it} &= \ln \left(e^{\beta T_{it}} A_{it} L_{it} \right) \\ &= \beta T_{it} + \ln A_{it} + \ln L_{it} \end{aligned}$$

- First difference

$$
\begin{aligned}
\ln Y_{it} - \ln Y_{it-1} &= \beta(T_{it} - T_{it-1}) + (\ln A_{it} - \ln A_{it-1}) \\
&\quad + (\ln L_{it} - \ln L_{it-1}) \\
\implies \ln \frac{Y_{it}}{Y_{it-1}} &= \beta(T_{it} - T_{it-1}) + \ln \frac{A_{it}}{A_{it-1}} + \ln \frac{L_{it}}{L_{it-1}} \\
\implies \ln \frac{Y_{it}}{Y_{it-1}} - \ln \frac{L_{it}}{L_{it-1}} &= \beta(T_{it} - T_{it-1}) + \ln(1 + \frac{\Delta A_{it}}{A_{it-1}}) \\
\implies \ln \frac{\frac{Y_{it}}{Y_{it-1}}}{\frac{L_{it}}{L_{it-1}}} &= \beta(T_{it} - T_{it-1}) + \ln(1 + \frac{\Delta A_{it}}{A_{it-1}})
\end{aligned}
$$

- Using equation (2) and logarithm approximation,

$$
\begin{aligned}
g_{it} &\approx \beta(T_{it} - T_{it-1}) + (g_i + \gamma T_{it}) \\
&= g_i + (\beta + \gamma) T_{it} - \beta T_{it-1}
\end{aligned}
$$

Suppose we treat this equation as a regression equation. Then start with

$$g_{it} = g_i + (\beta + \gamma)T_{it} - \beta T_{it-1}$$

and estimate

$$g_{it} = B_0 + B_1 T_{it} + B_2 T_{it-1} + \epsilon_{it}$$

If we can estimate this correctly, then $g_i = B_0$, $\beta = -B_2$ and $\gamma = B_2 + B_1$.

This leaves two questions: (1) How do we interpret β and γ? Why is one a ‘level’ and the other a ‘growth’ effect. (2) How can we estimate this equation?

To interpret β and γ, consider the following example:

$$(T_{i0}, T_{i1}, T_{i2}, T_{i3}, T_{i4}) = (0, 0, 1, 0, 0)$$
$$g_i = 0$$

Then using

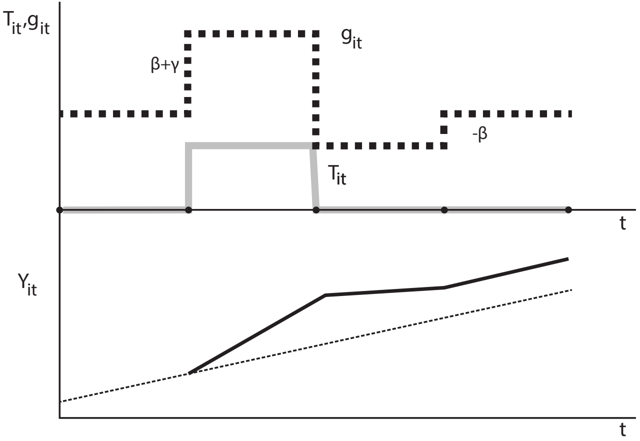
$$g_{it} = g_i + (\beta + \gamma) T_{it} - \beta T_{it-1}$$

we have

$$\begin{aligned}
g_{i0} &= \text{undefined, no temp at } t = -1 \\
g_{i1} &= 0 + (\beta + \gamma)0 - \beta(0) = 0 \\
g_{i2} &= 0 + (\beta + \gamma)1 - \beta(0) = \beta + \gamma \\
g_{i3} &= 0 + (\beta + \gamma)0 - \beta(1) = -\beta \\
g_{i4} &= 0 + (\beta + \gamma)0 - \beta(0) = 0
\end{aligned}$$

To see what this means for output, say $L_{it} = 1$ for all t and $Y_{i2} = 1$. Then we have,

$$
\begin{aligned}
Y_{i2} &= 1 \\
Y_{i3} &= (1 + g_{i2}) Y_{i2} \\
&= (1 + (\beta + \gamma)) \\
Y_{i4} &= (1 + g_{i3}) Y_{i3} \\
&= (1 - \beta)(1 + (\beta + \gamma)) \\
&= 1 + \beta + \gamma - \beta - \beta^2 - \beta\gamma \\
&\approx 1 + \gamma
\end{aligned}
$$



Top panel: Temperature is zero except from 1 to 2. g_{it} is g_i except between 1 and 3. Between 1 and 2, g_{it} is $g_i + \beta + \gamma$. Between 2 and 3, g_{it} is $g_i - \beta$. Bottom panel shows path of gdp. Without climate shocks it is dashed line. With climate it is solid line.

- β measures the effect of climate on the level of output. Here, if temperature changes, output changes, and if temperature reverts, so does output.
- γ measures permanent changes. If temperature changes, it changes the growth rate for that period, and this has a permanent effect on the level.

This is a very nice feature of 'distributed lag models'. They can distinguish level from growth effects.

Now consider the problem of estimating our distributed lag model:

$$g_{it} = B_0 + B_1 T_{it} + B_2 T_{it-1} + \epsilon_{it}$$

In order to understand inference problems, let's consider the simpler model without the lagged temperature term,

$$g_{it} = B_0 + B_1 T_{it} + \epsilon_{it}$$

Two problems that arise are

1. temperature and technology both trend upwards over time, so we'll confound the effects of progress with the effects of temperature.
2. country specific growth rates are correlated with temperature(slower growing countries are at the equator). This may reflect something other than climate.

Problem #1: Temperature and technology both trend upwards over time.

- If temperature trends up over time, we have

$$T_{it} = C_0 + C_1 t + \tau_{it}.$$

  t still indexes years, C_1 is the constant annual increase in T, and τ_{it} is country i's annual variation around the trend.

- If productivity trends upward over time then

$$\epsilon_{it} = D_i t + \mu_{it}.$$

  D_i is the constant annual contribution of technological progress to growth and μ_{it} the contribution of other unobserved factors to gdp growth for country i, year t.

This means that the true model describing the relationship between growth and temperature consists of three equations

$$\begin{aligned} g_{it} &= B_0 + B_1 T_{it} + \epsilon_{it} \\ T_{it} &= C_0 + C_1 t + \tau_{it} \\ \epsilon_{it} &= D_i t + \mu_{it}. \end{aligned}$$

Solving the second for t gives

$$t = (T_{it} - \tau_{it} - C_0)\frac{1}{C_1}$$

substituting this into the third equation gives,

$$\epsilon_{it} = D_i (T_{it} - \tau_{it} - C_0)\frac{1}{C_1} + \mu_{it}.$$

substituting this into the first equation gives

$$g_{it} = B_0 + B_1 T_{it} + D_i((T_{it} - \tau_{it} - C_0)\frac{1}{C_1}) + \mu_{it}$$
$$g_{it} = B_0 + (B_1 + \frac{D_i}{C_1})T_{it} + \left[\frac{(-\tau_{it} - C_0)D_i}{C_1} + \mu_{it}\right]$$

Thus, if we estimate

$$g_{it} = \hat{B}_0 + \hat{B}_1 T_{it} + \hat{\epsilon_{it}} \tag{3}$$

We'll end up with $\hat{B}_1 = B_1 + \frac{D_i}{C_1}$, and we confound the effects of technological improvement with temperature increases. Not at all what we want.

To see how to get around this, substitute the second and third equation of our model into the first,

$$g_{it} = B_0 + B_1(C_0 + C_1 t + \tau_{it}) + (D_i t + \mu_{it}).$$

Rearranging, we see that

$$g_{it} = (B_0 + B_1 C_0) + (B_1 C_1 + D_i)t + B_1(\tau_{it}) + \mu_{it}$$

If we estimate

$$g_{it} = \widehat{B}_0 + \widehat{B}_1 t + \widehat{B}_2 T_{it} + \widehat{\mu}_{it}.$$

then $\widehat{B}_0 = B_0 + B_1 C_0$, $\widehat{B}_1 = B_1 C_1 + D_i$, and $\widehat{B}_2 = B_1$, which means that we can estimate the coefficient on climate in this way.

Note the trick/theorem: we can substitute T_{it} for τ_{it} without affecting the coefficient of this variable.

Problem #2: What if hot countries grow slowly and experience faster(slower) temperature growth? In this case, it is initial level of heat that causes growth rate, not change. Note that hot countries tend to grow more slowly AND tend to be near the equator where climate is changing less rapidly.

To understand this problem, start by writing the math. Let

$$T_{it} = T_i + \tau_{it},$$

for $T_i = \frac{1}{50}\sum_{t=1}^{50} T_{it}$ is i's mean temperature. Also let

$$\epsilon_{it} = \mu_i + \eta_{it}.$$

where $\mu_i = \frac{1}{50}\sum_{t=1}^{50} \epsilon_{it}$ is country i's unobserved propensity to grow. We're worried that T_i and μ_i are both high/low at the same times, e.g. $T_i = D_0\mu_i$. In this case, we'd have $cov(T_{it}, \epsilon_{it}) \neq 0$.

Substituting the last two expressions into our basic estimating equation,

$$
\begin{aligned}
g_{it} &= B_0 + B_1 T_{it} + \epsilon_{it} \\
&= B_0 + B_1 (T_i + \tau_{it}) + (\mu_i + \eta_{it}) \\
&= (B_0 + B_1 T_i + \mu_i) + B_1 \tau_{it} + \eta_{it} \\
&= A_i \theta_i + B_1 \tau_{it} + \eta_{it}
\end{aligned}
$$

where θ_i is 1 for country i and zero otherwise. In this case, $A_i \theta_i$ reflects country i growth due to initial temperature and background rate of progress. B_1 measures the sensitivity of growth rate to deviations from temperature trend.

Combing the solutions to both problems, if we want to estimate

$$g_{it} = B_0 + B_1 T_{it} + \epsilon_{it}$$

then we should control for a country 'fixed-effect' and a time trend,

$$g_{it} = A_i \theta_i + B_1 t + B_2 \tau_{it} + \eta_{it}$$

Three more comments:

1. Dell et al actually let the estimate of B_2 vary by whether the country was in the top or bottom half of the country income distribution in 1950. You can (almost) think of this as splitting the sample and doing the regression twice, once on each sample.

2. The expression above uses conventional, very sloppy notation for country fixed effects. If $i = 0, 1$ then we should write

$$g_{it} = (A_0\theta_0 + A_1\theta_1) + B_1 t + B_2 T_{it} + \eta_{it}$$

or for $i = 1, \ldots N$,

$$g_{it} = \sum_{i=1}^{N} A_i\theta_i + B_1 t + B_2 T_{it} + \eta_{it}$$

instead of

$$g_{it} = A_i\theta_i + B_1 t + B_2 T_{it} + \eta_{it},$$

but almost nobody does.

3. Actually, Dell et al use annual indicator variables instead of a linear trend. This means that their estimating equation (their equation #4) is (almost)

$$g_{it} = \sum_{i=1}^{N} A_i \theta_i + \sum_{t=1}^{50} B_t \theta'_t + B_2 T_{it} + \eta_{it}$$

The first term is country fixed-effects, the second is year effects. Or, if they estimate a distributed lag model,

$$g_{it} = \sum_{i=1}^{N} A_i \theta_i + \sum_{t=1}^{50} B_t \theta'_t + \sum_{j=0}^{1} B_{2j} T_{it-j} + \eta_{it}$$

but they write it the sloppy/conventional way and consider more lags of temperature

$$g_{it} = A_i \theta_i + B_t \theta'_t + \sum_{j=0}^{k} B_{2j} T_{it-j} + \eta_{it}$$

Dell, Jones, Olken 2008

Dell, Jones, Olken 2008

Table 3: Models with lags

	(1) No lags	(2) 1 lag	(3) 3 lags	(4) 5 lags	(5) 10 lags	(6) No lags	(7) 1 lag	(8) 3 lags	(9) 5 lags	(10) 10 lags
Temperature × Poor	-1.087**	-0.954*	-0.932*	-0.933*	-1.112*	-1.074**	-0.945*	-0.925*	-0.925	-1.071*
	(0.442)	(0.559)	(0.560)	(0.562)	(0.586)	(0.446)	(0.558)	(0.557)	(0.559)	(0.585)
L1: Temperature × Poor		-0.351	-0.247	-0.328	-0.216		-0.330	-0.213	-0.333	-0.217
		(0.854)	(0.919)	(0.909)	(0.958)		(0.852)	(0.921)	(0.909)	(0.954)
L2: Temperature × Poor			-0.210	-0.183	-0.120			-0.249	-0.226	-0.140
			(0.441)	(0.459)	(0.485)			(0.443)	(0.458)	(0.484)
L3: Temperature × Poor			-0.216	-0.096	-0.231			-0.189	-0.075	-0.262
			(0.519)	(0.559)	(0.606)			(0.511)	(0.549)	(0.594)
Temperature × Rich	0.219	0.202	0.243	0.293	0.392	0.208	0.197	0.237	0.272	0.383
	(0.210)	(0.232)	(0.241)	(0.238)	(0.255)	(0.212)	(0.234)	(0.243)	(0.240)	(0.260)
L1: Temperature × Rich		0.047	0.074	0.094	0.093		0.038	0.067	0.083	0.056
		(0.268)	(0.251)	(0.252)	(0.268)		(0.269)	(0.250)	(0.252)	(0.266)
L2: Temperature × Rich			0.062	0.115	0.043			0.064	0.143	0.098
			(0.190)	(0.195)	(0.209)			(0.190)	(0.194)	(0.209)
L3: Temperature × Rich			-0.019	0.120	0.203			-0.045	0.097	0.211
			(0.197)	(0.186)	(0.198)			(0.197)	(0.185)	(0.197)
Includes precipitation vars.	NO	NO	NO	NO	NO	YES	YES	YES	YES	YES
Observations	6014	6014	5905	5785	5449	6014	6014	5905	5785	5449
R-squared	0.14	0.14	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Sum of all temp. coeff.	-1.087**	-1.304*	-1.605**	-1.718**	-2.006**	-1.074**	-1.275*	-1.576**	-1.662**	-1.946**
in poor countries	(0.442)	(0.677)	(0.641)	(0.720)	(0.866)	(0.446)	(0.689)	(0.651)	(0.737)	(0.881)
Sum of all temp. coeff.	-0.102	0.219	0.249	0.361	0.184	0.208	0.235	0.324	0.155	-0.147
in rich countries	(0.647)	(0.210)	(0.268)	(0.331)	(0.455)	(0.212)	(0.271)	(0.332)	(0.460)	(0.654)

Notes: All specifications use PWT data and include country FE, region × year FE, and poor x year FE. Robust standard errors in parentheses, adjusted for clustering at parent-country level. Sample includes all countries with at least 20 years of growth observations. Columns (6) – (10) also include Precipitation × Poor and Precipitation × Rich, with the same number of lags as the temperature variables shown in the table. Columns (4) and (9) also include the 4^{th} and 5^{th} lags of Temperature × Poor, Temperature × Rich, Precipitation × Poor and Precipitation × Rich. Similarly columns (5) and (10) also include the 4^{th} through 10^{th} lags of Temperature × Poor, Temperature × Rich, Precipitation × Poor and Precipitation × Rich; those coefficients are suppressed in the table to save space. Sum of all temperature coefficients in poor countries shows the sum (and calculated standard error) of Temperature × Poor and all of the lags of Temperature × Poor included in the regression; sum of all temperature coefficients in rich countries is calculated analogously.
* significant at 10%; ** significant at 5%; *** significant at 1%

- Recall, our simple distributed lag model

$$g_{it} = g_i + (\beta + \gamma)T_{it} - \beta T_{it-1}$$

The different between temperature coefficients for t and $t-1$ is the effect on growth per degree Celsius of warming.

- From Column 2 of table 3, for rich countries this is indistinguishable from zero. For poor countries it is about -1.3. SO 1 degrees of warming would give a $1 \times 1.3 = 1.3\%$ decrease in the growth rate. This estimate varies a little across specifications and is a bit bigger if we consider more lags.
- Rich country growth rates are 2-3%/year Country weighted annual growth rates were about 5% year for Africa between 2000-2010. My calculation, from OECD data

- This means that 1 degrees warming by 2100 causes about a 2% decrease in annual growth rate against 5% base, and climate change offsets half economic growth in poor countries! This is a huge effect.

Issues:

- Cross-sectional relationship between gdp and climate also shows a large negative relationship between temperature and gdp.
- These estimates deliberately only use short run variation in temperature and gdp, so there is no adaptation, e.g., changes in crops, This means it overstates effect of climate on growth. They try to address this, but ...
- Rich country findings consistent with Mendelsohn et al.
- general equilibrium effects,..., stay tuned.

Nonlinear temperature effects indicate severe damages to U.S. crop yields under climate change

Look at crop yields as a function of temperature for three most valuable US crops, corn, soybeans, cotton. (The US is the worlds biggest exporter of agricultural products).

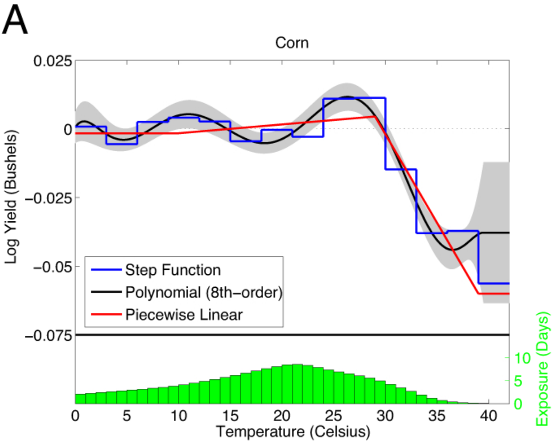
Data: crop yields by county for each crop, 1950-2005, and HOURLY temperatures and rainfall by county for the same period. Let $k = 1, .., K$ denote three degree Celsius 'bins', bin 1 [0,3), bin 2 [3, 6), etc. Assign each county hour to a bin according to it's temperature.

- D_{ikt} county i hours in temperature bin k in year t (really ln of hours).
- y_{it} county i year t yield of corn, soybeans, cotton, e.g., bu./acre.

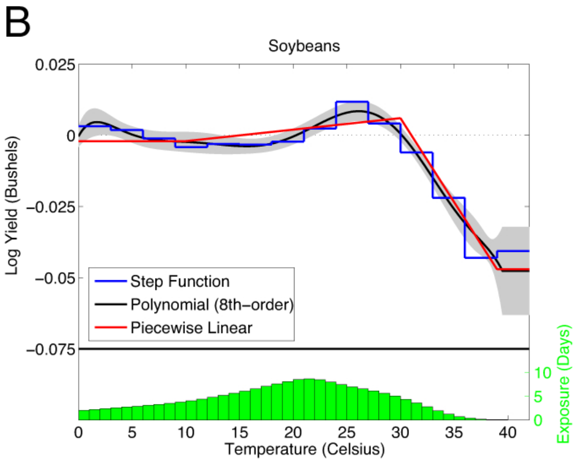
Now estimate,

$$y_{it} = B_1 D_{i1t} + B_2 D_{i2t} + ... + B_K D_{iKt} + A_0 + \epsilon_{it}.$$

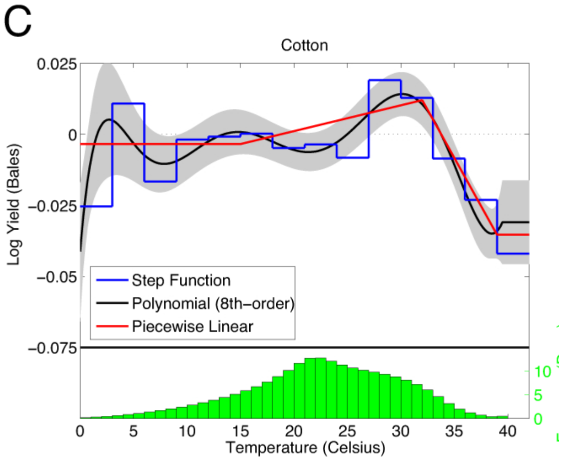
B_k is effect on yield of one extra hour of time in bin k averaged over counties and years.
If we plot the B_k against the temperature in bin k, we get...



Schlenker and Roberts, PNAS 2009 fig 1



Schlenker and Roberts, PNAS 2009 fig 1



Schlenker and Roberts, PNAS 2009 fig 1

Yields go down dramatically as exposure to high temperatures goes up. The threshold is 29-32 degrees Celsius.
Given these estimates, and projections for climate under different warming scenarios, we can ask what happens to yields as climate changes: reduction of 30-46% with lots of mitigation, 63-82% without.

Issues:

- We're estimating a production function, so endogeneity issue we discussed earlier is relevant. Maybe bad farmers buy land prone to hot spells?
- This is very short run. In particular, no crop substitution is allowed. Note that threshold for different crops is at different places, which suggests that crop substitution, from corn to soybeans and cotton would matter, maybe a lot.
- Mendelsohn et al also find evidence for non-linear effects of warming.
- Compare these results with the rapid adaptation that Rhode and Olmstead document

Climate and mortality I

This paper asks three main questions

- How does annual mortality vary with daily temperature? (Like Schlencker and Roberts)
- How does this relationship vary with country income?
- How does this relationship vary with long run average temperature?

These last two are about adaptation.

They use two main types of data:

- Vital statistics data reporting; year and country, ‘state’, and ‘county’ of death, age at death, for about 40 countries, about 1990-2010, and about 900k deaths.
- Gridded climate data for daily and long run temperature and rainfall.

To describe what they do, let i and t be county and year, and τ be day of year. Let $T_{it\tau}$ be daily temperature. For each county year, calculate

$$T_{it} = \frac{1}{365}\sum_{\tau=1}^{365} T_{it\tau}$$

$$T_{it}^2 = \frac{1}{365}\sum_{\tau=1}^{365} T_{it\tau}^2$$

$$T_{it}^3 = \frac{1}{365}\sum_{\tau=1}^{365} T_{it\tau}^3$$

$$T_{it}^4 = \frac{1}{365}\sum_{\tau=1}^{365} T_{it\tau}^4$$

So these are average, average squared, etc. The paper does everything with all four. To ease notation, I'll just use the first two.

In addition, let

$$\begin{aligned}
\mathit{TMEAN}_s &\sim \text{Long run state mean temp (e.g. 1990-2010)} \\
\ln(\mathit{GDPpc})_s &\text{Long run state mean GDP pc (e.g. 1990-2010)} \\
\alpha_{ai} &\sim \text{Age class} \times \text{county FE} \\
\delta_{act} &\sim \text{Age class} \times \text{country} \times \text{year FE} \\
\epsilon_{ait} &\sim \text{residual} \\
M_{ait} &\sim \text{Mortality per 100,000, age class } a\text{, county } i\text{, year } t
\end{aligned}$$

We can now state the paper's main regression

$$
\begin{aligned}
M_{ait} = {} & A_0 T_{it} + B_0 T_{it}^2 + \\
& B_0(TMEAN_s \times T_{it}) + B_1(TMEAN_s \times T_{it}^2) + \\
& C_0(\ln(GDPpc)_s \times T_{it}) + C_1(\ln(GDPpc)_s \times T_{it}^2) + \\
& \alpha_{ai} + \delta_{ct} + \epsilon_{ait}
\end{aligned}
$$

Here, the interaction terms tell us how the effect of the temperature changes with income and the long run temperature. That is they tell us about adaptation.

To understand how this works, drop the interaction terms and suppose the $A_0 = 0$ and $A_1 = 1$. Then this regression evaluates to

$$\begin{aligned} M_{ait} &= T_{it}^2 + \alpha_{ai} + \delta_{ct} + \epsilon_{ait} \\ &= \frac{1}{365} \sum_{\tau=1}^{365} T_{it\tau}^2 + \alpha_{ai} + \delta_{ct} + \epsilon_{ait} \end{aligned}$$

Suppose the first day of the year, $T_{it1} = 20$℃. If we swap this for a day $T'_{it1} = 35$℃. Then the resulting counterfactual annual mortality rate is

$$M'_{ait} = \frac{1}{365} \left(\sum_{\tau=1}^{365} T_{it\tau}^2 - 20^2 + 35^2 \right) + \alpha_{ai} + \delta_{ct} + \epsilon_{ait}$$

so that $M'_{ait} - M_{ait} = (-20^2 + 35^2)/365 = 2.55$. That is, swapping a 20℃ for a 35℃ increases all cause mortality per 100,000 by 2.55 per year.

We can do a similar exercise for 0℃ ... 34℃, and get the marginal effect of a change in each type of day. This lets us trace out a mortality-temperature relationship.

In fact, using the whole regression, we can trace out this relationship for different mortality/climate bins. This is exactly figure 1 in the paper.

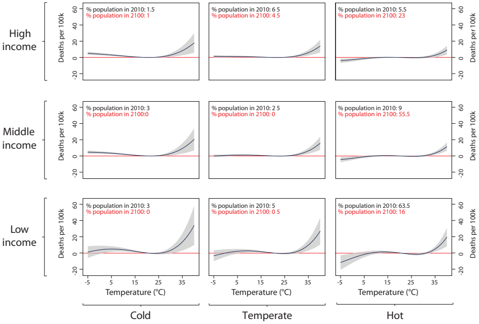


FIGURE I

Heterogeneity in the Mortality-Temperature Relationship (Age > 64 Mortality Rate)

Greenstone et al., QJE 2022

- Being rich is good (adaptation)
- Hot days are less harmful in hot places (adaptation)
- Getting rid of cold days in cold places reduces deaths
- In 2010 most people are in bottom right. In 2100, they will be middle or upper right.)

How can we use this to evaluate the mortality cost of climate change? First we have to specify a counterfactual climate, then use the response functions to evaluate the estimated change in mortality.

Our choice of sample matters a lot. We want to use the whole world, not the estimation sample of 40 countries.

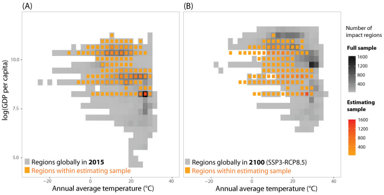


FIGURE II

Joint Coverage of Income and Long-Run Average Temperature for Estimating and Full Samples

Panels show the joint distribution of income and long-run average annual temperature in the estimating sample as compared to the global sample of impact regions. Panel A shows in gray-black the global sample for impact regions in 2015. Panel B shows in gray-black the global sample for impact regions in 2100 under a high-emissions scenario (RCP8.5) using climate model CCSM4 and a median-growth scenario (SSP3). In both panels, the estimating sample indicates coverage for impact regions in the estimating sample using 2015 values of income and long-run average annual temperature.

Greenstone et al., QJE 2022

Our decision about whether to allow income growth is important (interaction terms with income) and adaptation (interaction terms with long run temperature are also important. Allowing for both, this is what we get (Africa is the big loser.)

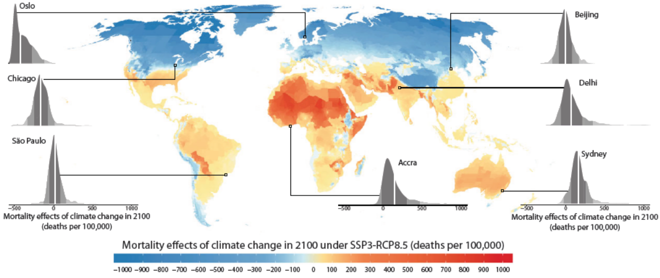


FIGURE IV

The Mortality Effects of Future Climate Change

The map indicates estimates of the mortality effects of climate change (equation (2′)), measured in units of deaths per 100,000 population, in 2100. Estimates come from a model accounting for the benefits of adaptation and income growth, and the map shows the climate model weighted mean estimate across Monte Carlo simulations conducted on 33 climate models; density plots for select regions indicate the full distribution of estimated effects across all Monte Carlo simulations. In each density plot, solid white lines indicate the mean estimate shown on the map, while shading indicates 1, 2, or 3 standard deviations from the mean. All values shown refer to the RCP8.5 emissions scenario and the SSP3 socioeconomic scenario. See Online Appendix Figure F.6 for an analogous map of effects for RCP4.5 and SSP3.

Greenstone et al., QJE 2022

If we average over all places within a year, and along all years from now to 2100, this is global average change in mortality. Adaptation and inclome growth can help a lot, but a lot more people live in hot places than cool, so the total effect is still to increase mortality.

Greenstone et al. (2023)

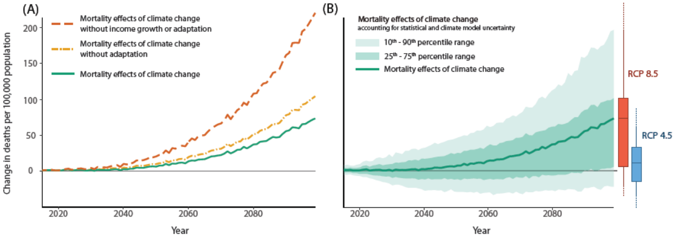


FIGURE V

Time Series of Projected Mortality Effects of Climate Change

All lines show projected mortality effects of climate change across all age categories and are represented by a mean estimate across a set of Monte Carlo simulations accounting for climate model and statistical uncertainty. In Panel A, each line represents one of three measures of the mortality effects of climate change. Dashed (equation (2a′)): mortality effects of climate change without income growth or adaptation. Dashed-dotted: (equation (2b′)): mortality effects of climate change without adaptation. Solid (equation (2′)): mortality effects of climate change. Panel B shows the 10th–90th percentile range of the Monte Carlo simulations for the mortality effects of climate change (equivalent to the solid line in Panel A), as well as the mean and interquartile range. The boxplots show the distribution of mortality effects of climate change in 2100 under both RCPs. All line estimates shown refer to the RCP8.5 emissions scenario and all line and boxplot estimates refer to the SSP3 socioeconomic scenario. Online Appendix Figure F.7 shows the equivalent for SSP3 and RCP4.5.

Greenstone et al., QJE 2022

How do we turn this into something we can use in our models? We need to convert deaths to dollars. For this we the ‘Value of a Statistical Life’. This is a number estimated by looking at how people exchange, e.g., wages for risky jobs. The current estimates for this are about 10m$ for the US and a little less for poorer countries.

Table 2 in the paper reports this estimate at about 3% of GDP under RCP8.5.

Issues: (1) No migration. (2) No changes to patterns of trade. We will see evidence shortly to suggest these things are important.

The relationship between climate and future consumption I

- Projections used in Stern and Nordhaus models predict about 3% decline in the level gdp for 3 degrees of warming, with variation between 0-6% (more or less). For more warming, damage goes up fast.
- These projections are predominantly based on studies like the Mendelsohn et al study.
- Pay attention to time scale when reading, e.g., Stern and Hansen. Catastrophes seem to start with 5+ degrees of warming, which is probably 200 years away. IPCC and Nordhaus focus on 100 year horizon.

The relationship between climate and future consumption II

- There is reason to be suspicious of these forecasts. Dell et al find large effect of climate on growth rates for poor countries. Schlenker and Roberts find big effects on yields past a certain temperature threshold.
- Greenstone et al. finds big effects, but does not allow for migration or trade.
- With this said, it is striking that there is so little agreement in the literature on the SIGN of the effects of climate change. This suggests to me that, in fact, the effects are small for developed countries.

The relationship between climate and future consumption III

Recalling our statement of the global warming problem,

$$\max_{I,M} u(c_1, c_2) \tag{4}$$

$$\text{s.t. } W = c_1 + I + M \tag{5}$$

$$c_2 = (1 + r)I - \gamma(T_2 - T_1)I \tag{6}$$

$$E = (1 - \rho_4 \frac{M}{W})(\rho_5(c_1 + I)) \tag{7}$$

$$P_2 = \rho_0 E + P_1 \tag{8}$$

$$T_2 = \rho_1(P_2 - P_1) + T_1 \tag{9}$$

We're after γ.

The relationship between climate and future consumption IV

With no warming then the second constraint above is

$$c_2^A = (1 + r)I$$

with three degrees of warming it is,

$$c_2^B = (1 + r)I - \gamma s3.$$

The relationship between climate and future consumption V

If a 3 degree increase in temperature decreases output by 3% then $c_2^A = 0.97c_2^B$. Using these relationships, we have

$$
\begin{aligned}
0.97c_2^A &= c_2^B \\
0.97c_2^A &= (1+r)I - \gamma(3)I \\
\implies 0.97[(1+r)I - \gamma(0)I] &= (1+r)I - \gamma(3)I \\
\implies 0.97[(1+r)I] &= (1+r)I - \gamma(3)I \\
\implies 0.01(1+r) &= \gamma
\end{aligned}
$$

So γ is about 0.01. (But Nordhaus et al generally use a non-linear relationship like the ones I plotted earlier). The results in Greenstone et al. would about double these damages.

Future consumption price of current emissions I

Here is how we can use all of these numbers to try to guess at the future consumption price of current emissions:

- Current world gdp is about 7.7×10^{13} (77 trillion) 2010 USD
- If the world economy grows at 3%/year for the next 100 years, world gdp will be $7.7 \times 10^{13} \times (1.03)^{100} = 15 \times 10^{14}$ 2010USD.
- 3% of this amount is 4.5×10^{13}\$
- 3 degrees of warming causes a 3% decrease in the level of gdp (about)
- 3 degrees of warming is caused, in 100 years, by doubling CO_2 concentrations from 280 to 560ppm.

Future consumption price of current emissions II

- Each ppm of concentration requires 2.12 Gt C in the atmosphere and 3.8 Gt C emissions. So increasing atmospheric concentrations of CO_2 to 560 ppm requires $280 \times 3.8 = 1064$ Gt C emissions.
- Thus, 1064 Gt C of emissions causes a loss of 4.5×10^{13}\$ in 100 years.
- Dividing, 1 Gt C causes about 4.2×10^{10}\$ damages.
- Thus, 1 t C causes about $4.2 \times 10 = 42$\$ of damages in 2100 (and in 2101, 2012, ...).
- 1 t CO_2 emissions results from 435 liters of gasoline. Thus, we get about 1/3.7 t C emissions from 435 liters. It follows that a 50 liter tank of gas causes about. $\frac{50}{435} \times \frac{1}{3.7} \times 42 = 1.40$\$ of damage in 2100 (and 2101, 2012,....).

Future consumption price of current emissions III

What we're doing here is to use the four constraints in our model to solve for future consumption as a function of emissions.
The next step is to compare present and future consumption.