Lecture Notes on Damages

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IIES

May 2020

Purpose today

- Give examples of different approaches to measuring and aggregating damages of climate change.
- Climate change is a global phenomenon and affects the economy in a large number of ways.
- Two ways to estimate total effects:
  - bottom up – quantifying all potential effects and summing.
  - reduced form – looking at correlation between natural variation in climate and variables like GDP, productivity, political stability and others.
- Approaches have different pros and cons. Complementary.

Nordhaus damages in RICE– a bottom up approach

- Divide effects into: 1. Agriculture, 2. Sea-level rise, 3. Other market sectors, 4. Health, 5. Non-market amenity impacts, 6. Human settlements and ecosystems, 7., Catastrophes.
- 13 regions; U.S., OECD Europe, Eastern Europe, Japan, Russia, China, Africa, India, Other high income, Other middle, Other low middle income, Low income, and High Income OPEC.

Functional specification

- For each sector and region, collect studies on how climate change affects the economy.
- Use studies to specify and calibrate a damage function. This specifies how climate change (represented by change in global mean temperature) affects damages to output/capital stocks or willingness to pay for non-market items. All is measured as % of GDP.
- For each region, sum over sectors.
- Produces a damage function for each region j, $D^j(T)$ .Damages in region j as a function of the (increase in) the global mean temperature T.
- By summing over regions, a global damage function is constructed $D(T)$, % of GDP lost as a function of global mean temperature.

Example agriculture

- Most studied. Damage depends on; CO_2, temperature, precipitation and adaptation.
- Nordhaus summarizes various studies of effects on agriculture

Table 4-4.
Estimated Damages on Agriculture from CO2 Doubling
[Benefits are negative while damages are positive]

	Billions, 1990 US dollars	% of GDP
United States [a]	3.90	0.07
China [a, b]	-3.00	-0.51
Japan [a]	-17.20	-0.55
OECD Europe [a]	42.10	0.58
Russia [c]	-2.88	-0.87
India [d]	5.11	1.54
Other High Income [a, e]	-10.40	-1.14
High-Income OPEC [f]	0.00	0.00
Eastern Europe [g]	2.26	0.58
Middle Income [h]	19.51	1.43
Lower-Middle Income [l]	0.65	0.06
Africa [l]	0.10	0.06
Low Income [l]	0.30	0.06

- He finds effects that tend to be positive if initial temperature is below 11.5 degrees, negative otherwise.

Quadratic damage function

- The non-monotonic effects of T suggests quadratic damage function

$$D^j(T) = \alpha^j_{ag} + \alpha_{1,ag}\left(T + T^j_0\right) + \alpha_{2,ag}\left(T + T^j_0\right)^2$$

- Here, superscript j indicates region. T^j_0 is initial temperature and α^j_{ag} a country specific constant. $\alpha_{1,ag}$ estimated to be positive and $\alpha_{2,ag}$ negative. Marginal effect of increase in T given by

$$\frac{\partial\left(\alpha^j_{ag} + \alpha_{1,ag}\left(T + T^j_0\right) + \alpha_{2,ag}\left(T + T^j_0\right)^2\right)}{\partial T} = \alpha_{1,ag} + 2\alpha_{2,ag}\left(T + T^j_0\right).$$

Thus, the effect is negative if $\left(T + T^j_0\right) > \frac{\alpha_{1,ag}}{2\alpha_{2,ag}}$.

Other sectors

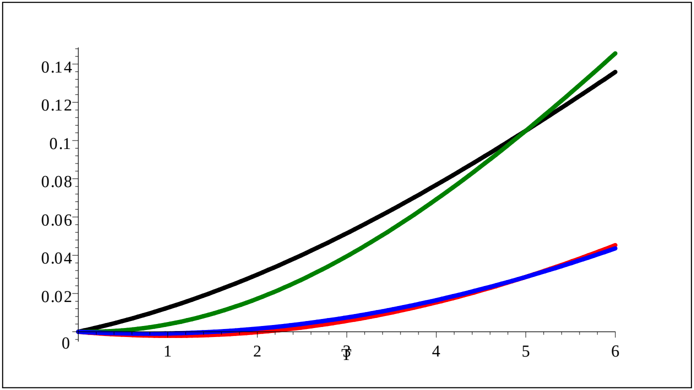
- Similar approach but typically less studies to rely on.
- Does not add up to very much for a temperature increase of 2.5 degrees. Global population weighted values damages at 2.5 degrees, Ag =0.17%, Other m =0.23%, Coast =0.12%, Health 0.56%, Non-market -0.03, Settlem. 0.1.
- Large heterogeneity. Over 1% loss in agriculture in India and Lower middle Income (Brazil and others). 3% loss due to health in Africa.
- Total damage zero or negative in U.S. and China. Large (around 3%) in Africa and India.
- Catastrophic impacts added.

Catastrophe

- Survey to experts. "What is the probability of permanent 25% loss in output if global warming is 3 and 6 degrees respectively?"
- Varied answers with mean 0.6 and 3.4%. (median 0.5 and 2.0). Arbitrarily doubled and damage increased to 30% globally.
- Distributed over regions reflecting different vulnerability.
- Assuming risk aversion of 4 translated into willingness to pay to avoid risk.
- Leads to 1.02% and 6.94% WTP for 2.5 and 6 degrees warming globally.
- India twice as willing, US and China less than half.

Nordhaus aggregate damage

- Damages as percent of GDP, described by $D^j(T) = 1 - \frac{1}{1+\theta_1^j T + \theta_2^j T^2}$ with region-specific $\theta^j s$ (Blue-USA, Red-Chi, Green-Eur, Black-LI).



Nordhaus (2013)

- Goes back to more ad hoc description. Global damages

$$D(T) = 1 - \frac{1}{1 + 0.00267T^2} \approx 0.023\left(\frac{T}{3}\right)^2$$

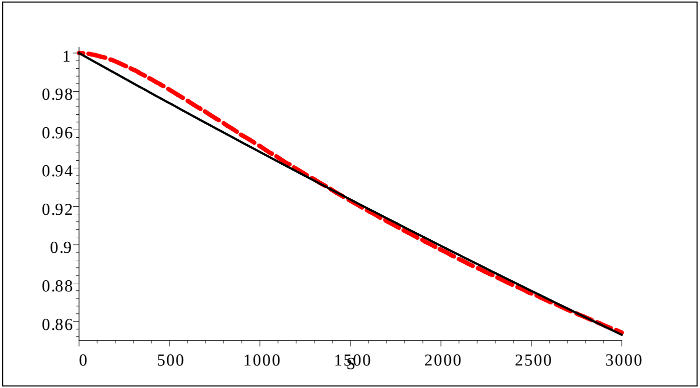
- Also allows a term in T^3 producing more convex damages.
- Other models have included even larger exponents on T.
- The model FUND uses a *random exponent* from the interval 1.5-3.
- Weitzman (2010) has an exponent of 6.8.
- Nordhaus stresses that damage function for high temperatures ($>$3 or 4 degrees?) should not be taken very seriously.

Damages of carbon (Golosov et al. 2014)

- Nordhaus's aggregate damage function maps temperature into damages.
- Now consider the two steps from increased CO_2 concentration (S) to the change in global mean temperature (T) and from T to damages together. $S \rightarrow T \rightarrow D$.
- For the first step $S \rightarrow T$ use Arrhenius $T(S) = \frac{3}{\ln 2} \ln\left(\frac{S+600}{600}\right)$ where S is GtC over the pre-industrial level (600 GtC). Dynamics are disregarded.
- For the second $T \rightarrow D$, we used Nordhaus' global damage function $D(T)$.
- Together, the two steps are $D(T(S))$ mapping additional atmospheric carbon to damages.

Simplification of Nordhaus

- It turns out that $1 - D\left(T\left(S\right)\right)$, i.e., how much is left after damages as a function of S, is well approximated by the function $e^{-\gamma S}$ for $\gamma = 5.3 * 10^{-5}$ (black) and $1 - D\left(T\left(S\right)\right)$ (red dashed) as seen in the figure.



Exponential function very convenient

- Define Y_{net} as output net of damages and Y as gross output, implying $Y_{net} = (1 - D(T(S)))Y$.
- Using the approximation $(1 - D(T(S))) \approx e^{-\gamma S}$, $Y_{net} = e^{-\gamma S}Y$.
- Then, $\frac{\partial Y_{net}}{\partial S}\frac{1}{Y_{net}}$ is the marginal loss of net output from additional GtC in the atmosphere expressed as a share of net output.
- Using our approximation, we have $\frac{\partial Y_{net}}{\partial S}\frac{1}{Y_{net}} = \frac{\partial\left(e^{-\gamma S}Y\right)}{\partial S}\frac{1}{e^{-\gamma S}Y} = -\gamma$, i.e., marginal losses are a constant proportion of GDP!
- Marginal damage flow independent of GDP and CO_2 concentration.
- With $\gamma = 5.3 * 10^{-5}$ one GtC extra in the atmosphere gives extra damages at 0.0053%. Recall the rate of accumulation of S_t.
- Robust?

Ciscar et al. PNAS Feb 2011

- Another bottom-up study, but for Europe only.
- Sums the impact for 5 types of damages; agriculture production, river floods, coastal effects, tourism (market) and health.
- Use different high-resolution models 50x50 km, and use distribution of weather outcomes, not only temperature.
- Compare different scenarios for year 2080 to baseline of no climate change.
- For EU as a whole yearly damages equivalent to 1% of consumption for 5.4 degree heating in EU. Small positive effects on tourism and substantial positive effects on Northern Europe.
- Relative to growth rate over 70 years ($1.02^{70} \approx 4$), these effects seem fairly small.

Survey Nordhaus and Moffat (2017)

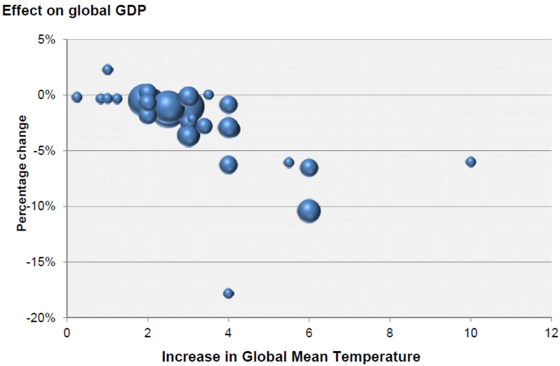


Figure: Metastudy of studies on effects of climate change. Area of ball indicates reliability judged by Nordhaus and Moffat.

Survey Howard&Sterner (2017)

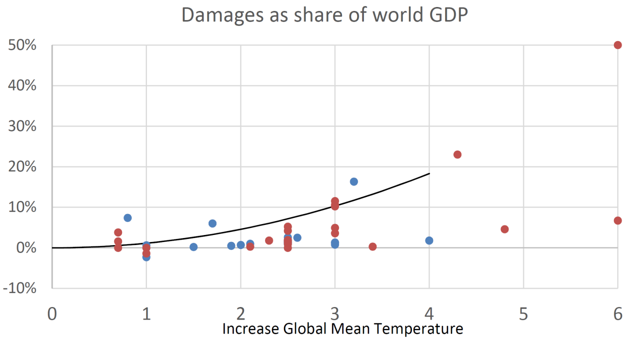
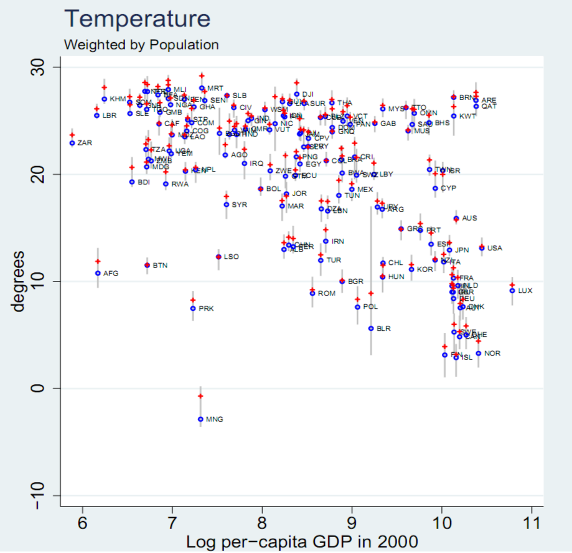


Figure: Metastudie H&S Red dots are non-duplicate studies and line is prefered regression.

Reduced form

- Idea is to use natural temporal variation in climate and correlate with economic outcomes – natural experiments.
- Microstudies on agriculture, labor productivity, industrial output, health and mortality, conflicts and stability, crime, ... See Dell, Jones and Olken, "What Do We Learn from the Weather? The New Climate-Economy Literature," (Journal of Economic Literature, 2014)
- Microstudies yield credible identification but little external validity and no general equilibrium effects.
- Fewer aggregate reduced form studies. One of few: Dell, Jones and Olken. American Economic Journal: Macroeconomics (2008).
- Monthly data on weather from 1900, 0.5 degree spatial resolution (interpolation) (use 50 last yearly obs.). Economic data from Penn World Tables, 136 countries.



Blue circle (red plus) is mean temp in 1950-1959 (1996-2005). Gray lines is range of annual temperature over sample period.

Dell, Jones and Olken (2012)

- Assume

$$\begin{aligned} Y_{it} &= e^{\beta T_{it}} A_{it} L_{it};\ \beta \text{ captures level damage} \\ \frac{\Delta A_{it}}{A_{it}} &= g_i + \gamma T_{it};\ \gamma \text{ captures growth rate damage} \end{aligned}$$

- Estimate parameters in panel regression (125 countries, 1950-2005) including lags.
- Strong effects on growth – one degree higher temperature leads to 1% less growth.
- But only in poor countries (below median at start).
- Persists for at least 10 years.
- Similar results for industrial output, aggregate investment and political stability.
- Tentative conclusion – climate change is a big problem for countries that do not become sufficiently rich.

Kahn, Mohaddes, Ng, Pesaran, Raissi, Yang (2019)

- Panel estimate (174 countries, 1960-2014) of

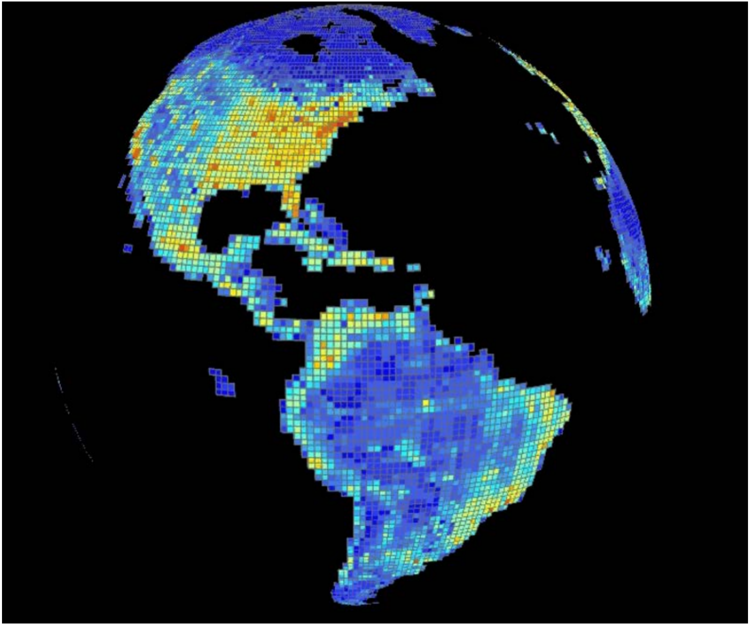
$$\Delta y_{i,t} = a_i + \sum_{l=1}^{p} \varphi_l \Delta y_{i,t-l} + \sum_{l=0}^{p} \beta_l^{+} \Delta \left(T_{i,t-l} - \bar{T}_{i,t-l} \right)^{+} + \sum_{l=0}^{p} \beta_l^{-} \Delta \left(T_{i,t-l} - \bar{T}_{i,t-l} \right)^{-} + \varepsilon_{i,t},$$

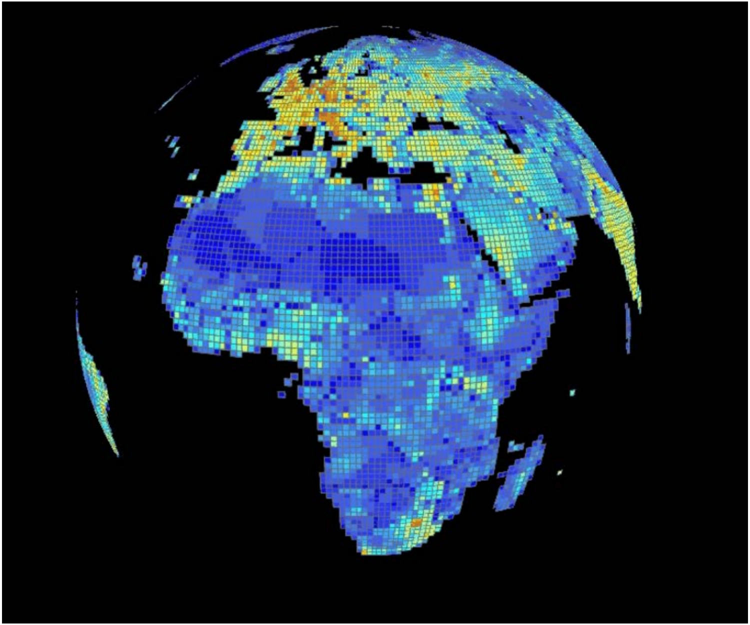
  where $\Delta y_{i,t}$ is output growth in country i, $T_{i,t}$ is yearly average temperature in country i and $\bar{T}_{i,t-l}$ is 30 year average.

- Results:
  - Increasing and decreasing temperature has same negative effect. Status quo bliss.
  - No significant difference between rich and poor, or hot and cold.
  - Effect non-trivial. 0.01 degrees per year, reduces growth by 0.06% (with no rebound).
  - BAU leading to 4 degrees higher GMT by 2100 (0.04 degrees/year increase) reduces global GDP by 7%.

Temperature - GDP with high resolution data

- Unit of analysis: $1^\circ \times 1^\circ$ global grid (land). 19,000 regions (cells).
- Nordhaus G-Econ database: GDP and population for all cells in 1990, 1995, 2000 and 2005.
- Produces nice charts!

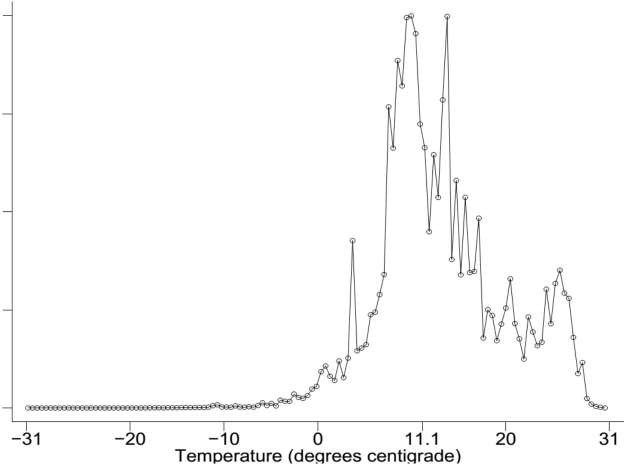




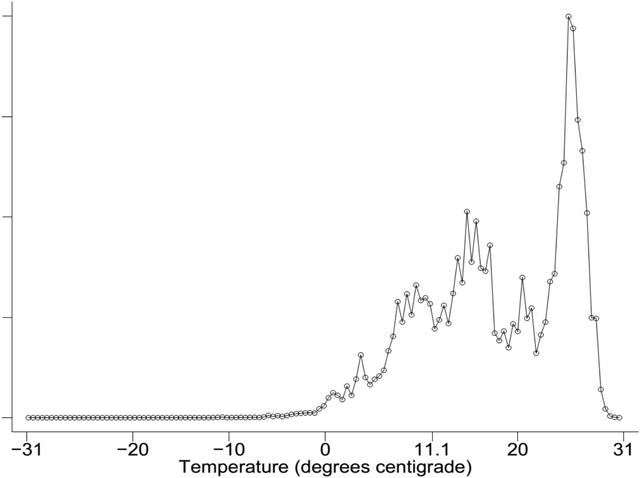
Climate data and projections

- Temperature data exists on same $1^\circ \times 1^\circ$ global grid.
- Assume relation between GDP and temperature is not random but reflects causal relationship. Use to assess consequences of changes in temperature.
- Obvious *pros* as well as *cons* with this methodology.

Share of Global GDP vs Yearly Mean Temp



Share of Global Population vs Yearly Mean Temp



- Climate change affects regions very differently. Stakes big at regional level.
- Though a tax on carbon would affect welfare positively in some average sense, huge disparity of views: 55% of regions hurt, 45% benefit from climate change.
- Strong migration pressures from climate change.

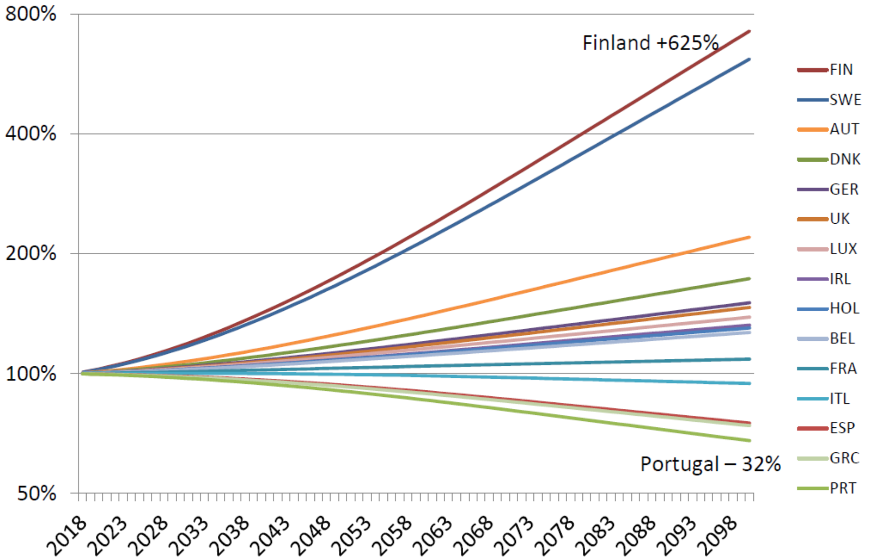
Dangerous to use model-free econometrics?

- A model is a way of imposing discipline on predictions.
- Predictions based on empirical analysis without model can be dangerous.
- Recent example: Burke, Davis, Diffenbaugh, *Nature 2018.*
- Estimates effects of temperature on national GDP per capita growth rates from a panel regression with yearly observations on growth and temperature (country fixed effects and quadratic time trends).

$$\Delta y_{i,t} = \beta_1 T_{i,t} + \beta_2 T_{i,t}^2 + \mu_i + \nu_t + \gamma_1 t + \gamma_2 t^2 + \varepsilon_{it}$$

- Finds $\beta_1 > 0, \beta_2 < 0$. Growth increases (decreases) in temperature if temperature is below (above) 13 degrees. Uses the estimates to project the long-run consequences of global warming.
- Gives nonsensical results out of line with growth facts.
- I used their estimates to look at consequences for EU of an increase in the Global Mean Temperature by 2.5 degrees (peaking at 2080).

Consequences of 2.5 degrees increase in GMT for EU15



Conclusion

- Empirical support for substantial effects on the economy from climate change.
- Effects can be large in particular regions.
- Evidence does not clearly point towards very large aggregate effects for moderate heating (<3 degrees). But substantial uncertainty and heterogeneity.
- Very little is known for more extreme scenarios.
- At least for moderate heating marginal damage per unit of extra ton in atmosphere may be approximately constant.
- Much to be learnt from further research.