Lecture Notes on Climate Damages

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Purpose today

- Discuss different effects of climate change.
- 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 across time or regions and variables like GDP, productivity, political stability and others.
- Approaches have different pros and cons. Complementary.

Starting points

- What kind of effects of climate change should be included?
- **Answer:** In principle everything that effects (human) welfare anywhere and at any time!
- Thinking of policy implications (optimal taxes), effects need to be aggregated into one summary measure. Recall that optimal tax should equal sum of all externalities per unit of emitted carbon.
- Requires a common metric – dollars if tax is in dollars. Aggregation of effects also facilitates building IAM's.
- Even if everything is measured in dollars (often expressed as a share of GDP), the direct effect on measured GDP is probably just a small part of what should be included in the damage estimates.

Types of effects

- Some effects can be quantified using market prices.
  - E.g., storm and flooding damages, changes in land values and in agricultural productivities.
- Some are in principle measurable but hard to estimate.
  - E.g., changes in economic ecosystem services due to less biodiversity.
- Others are more difficult to measure but are commonly priced in standard Cost-Benefit analyses.
  - E.g., effects on health and mortality.
- Others yet are even more difficult to measure and subjective.
  - E.g., distributional effects (across and within generations).
  - Cost of extinction of species like polar bears over and above their direct value in providing monetized ecosystem services.
  - Cost of possible political instability and mass-migration.

Who should set the price on different damages?

- Putting prices on different effects of climate change so that different effects can compared and aggregated cannot be done without value judgments (preferences).
- In principle, this is true for basically everything economists due. For example, we aggregate the value of production of all kinds of goods and services into GDP. How is this done?
- As economists we typically refrain from taking a stand on whether apples are worth more than pears, or opera better than rap.
- We let "the market" decide. Thus, we use preferences of individuals as revealed by market prices. Similarly, we assess the value of consuming now versus in the future by observing the real interest rate.

Market prices or moral judgements?

- Should we use market prices if possible when it comes to climate damages?
- Long discussion between e.g., Stern and Nordhaus.
  - Stern argues that it is "immoral" to use the subjective discount rates that can be extracted from market interest rates when evaluating the welfare of future generations. Yields an optimal carbon tax that is immorally low. Similarly, one can argue that it is "immoral" to assign a lower value of life and health of people in low-income countries than in high-income.
  - Nordhaus argues that i) models should be able to replicate what we see in reality, ii) economist have no particular expertise in talking about what is morally right, and iii) there are also many other ways of helping the poor and future generations than reducing climate change.

My view

- Largely on the side of Nordhaus, but;
  - I think also economists are allowed to take a stand on what is morally right, perhaps they even should. Such statements can and should be separated from positive analysis.
  - When constructing IAM's for positive purposes, we need to use market prices, e.g., market interest rates. Otherwise models are inconsistent with reality.
  - "Optimal taxes" based on these prices are not necessarily the right policy recommendation. We may collectively want to give more weight to the welfare of future generations than what market participants do.
  - But, other tools to achieve goals like more equality and better outcomes for future generations should not be excluded from the recommendations.

First attempt to assess climate damages

- In the early 90's, Nordhaus constructed the first IAM and thus had to quantify and aggregate climate damages.
- He used a bottom-up approach.
- Effects divided 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 s and region r, collect studies on how climate change affects the economy.
- Use studies to specify and calibrate damage functions $D^{s,r}(T)$. 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 $D^r(T) = \sum_s \theta_{s,r} D^{s,r}(T)$ where $\theta_{s,r}$ is share of GPP of sector s in region r.
- Produces a damage function for each region r, $D^r(T)$ .Damages in region r as a function of the the global mean temperature T.
- By summing over regions, $D(T) = \sum_r \theta_r D^{s,r}(T)$ where θ_r is share of global GPP in region r, a global damage function can constructed $D(T)$. Gives % of GDP lost as a function of global mean temperature.
- Since the global mean temperature T is an (almost) sufficient statistic of climate change, we need only T as argument.

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 [I]	0.65	0.06
Africa [I]	0.10	0.06
Low Income [I]	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

$$D^{ag,r}(T) = \alpha^r_{0,ag} + \alpha_{1,ag}\left(T + T^r_0\right) + \alpha_{2,ag}\left(T + T^r_0\right)^2$$

- Here, superscript r indicates region. T^r_0 is initial regional temperature and T the global mean temperature. $\alpha^r_{0,ag}$ is a region specific constant. The other parameters common to all $\alpha_{1,ag}$ are estimated to be negative and $\alpha_{2,ag}$ positive. Marginal effect of increase in T given by

$$\begin{aligned} & \frac{\partial\left(\alpha^r_{ag} + \alpha_{1,ag}\left(T + T^r_0\right) + \alpha_{2,ag}\left(T + T^r_0\right)^2\right)}{\partial T} \\ = \; & \alpha_{1,ag} + 2\alpha_{2,ag}\left(T + T^r_0\right). \end{aligned}$$

Thus, damages are increasing in temperature if $\left(T + T^r_0\right) > -\frac{\alpha_{1,ag}}{2\alpha_{2,ag}}$.

Other sectors

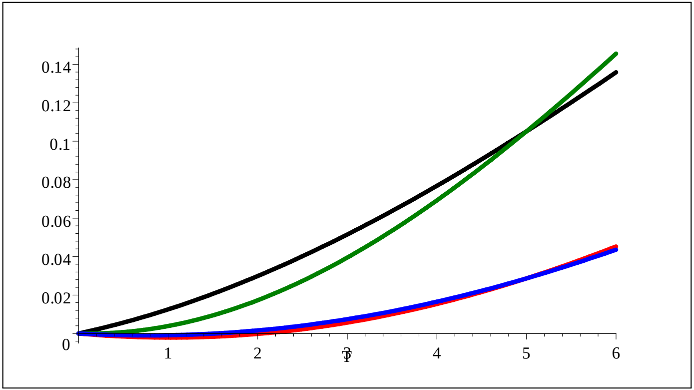
- Similar approach but typically less studies to rely on.
- Did not add up to very much for a temperature increase of 2.5 degrees. Global population weighted values damages at 2.5 degrees, Ag =0.17%, Other m =0.23%, Coast =0.12%, Health 0.56%, Non-market -0.03, Settlem. 0.1.
- Large heterogeneity. Over 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, approximately captured by $D^r(T) = 1 - \frac{1}{1+\theta_1^r T + \theta_2^r T^2}$ with region-specific $\theta^r s$ (Blue-USA, Red-Chi, Green-Eur, Black-LI).



Nordhaus (2013)

- Goes back to more ad hoc description. Global damages

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

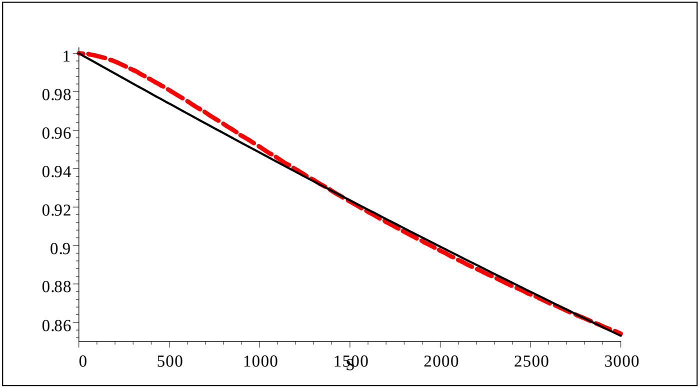
- Also allows a term in T^3 producing more convex damages.
- Other models have included even larger exponents on T.
- The model FUND uses a *random exponent* from the interval 1.5-3.
- Weitzman (2010) has an exponent of 6.8.
- Nordhaus stresses that damage function for high temperatures ($>$3 or 4 degrees?)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

Damages of carbon (Golosov et al. 2014)

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

Simplification of Nordhaus

- It turns out that $1 - D\left(T\left(\hat{S}\right)\right)$, i.e., how much is left after damages as a function of $\hat{S}$, is well approximated by the function $e^{-\gamma\left(\hat{S}\right)}$ for $\gamma = 5.3 * 10^{-5}$ (black) and $1 - D\left(T\left(\hat{S}\right)\right)$ (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 $Y_{net} = \left(1 - D\left(T\left(\hat{S}\right)\right)\right) Y$.
- Using the approximation $\left(1 - D\left(T\left(\hat{S}\right)\right)\right) \approx e^{-\gamma \hat{S}}$, $Y_{net} = e^{-\gamma \hat{S}} Y$.
- Then, $\frac{\partial Y_{net}}{\partial \hat{S}} \frac{1}{Y_{net}}$ 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 $\frac{\partial Y_{net}}{\partial \hat{S}} \frac{1}{Y_{net}} = \frac{\partial\left(e^{-\gamma \hat{S}} Y\right)}{\partial \hat{S}} \frac{1}{e^{-\gamma \hat{S}} Y} = -\gamma$, i.e., every additional unit of carbon in atmosphere yields a constant percentage reduction in 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?

Peseta project

- Bottom-up study, but for Europe only. Large group of experts financed by EU Commission.
- Consequences for 11 categories including: heat waves, windstorms, droughts, flooding, wildfires, agriculture and energy supply.
- Use different high-resolution models 50x50 km, and use distribution of weather outcomes, not only temperature.
- Results: non-trivial but non-catastrophic impacts if 2 or 3 degrees global warming would hit our current society (so no adaptation). Aggregate cost for EU around a percent of GDP. Similar to IPCC reporting 0.2-2% GDP losses from 2° warming.
- Increased mortality due to heat-waves and flood damages largest but not only concern. Creating resilience (adaptation) very important. Can reduce damages by an order of magnitude.
- Substantial differences within EU. North not much affected.
- "displacement of people, conflicts and security, the irreversible damage to nature and species losses, and the potentially daunting consequences of passing climate tipping points" not accounted for.

Results from Peseta IV

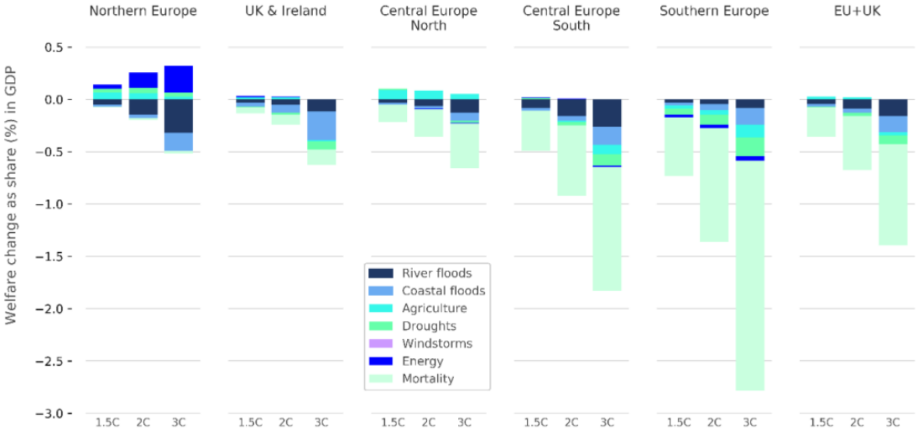


Figure 31. Welfare loss (% of GDP) from considered climate impacts at warming levels for the EU and the UK, and for macro regions (see Approach). The results represent change in welfare if warming levels would act upon current economy, compared to current economy under present climate.

Survey Nordhaus and Moffat (2017)

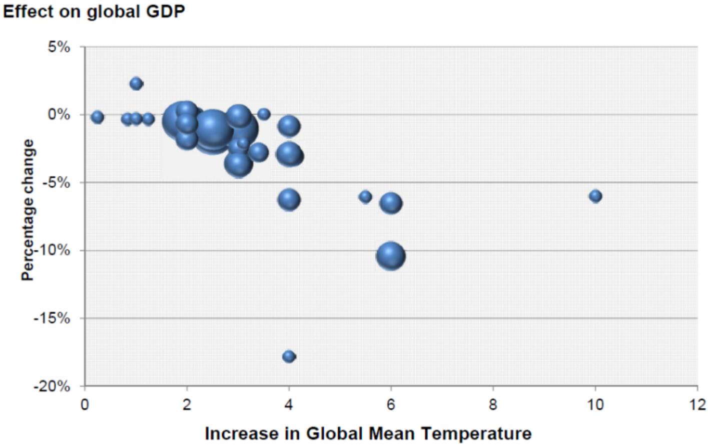


Figure: Metastudy of studies on effects of climate change. Area of ball indicates reliability judged by Nordhaus and Moffat.

Survey Howard&Sterner (2017)

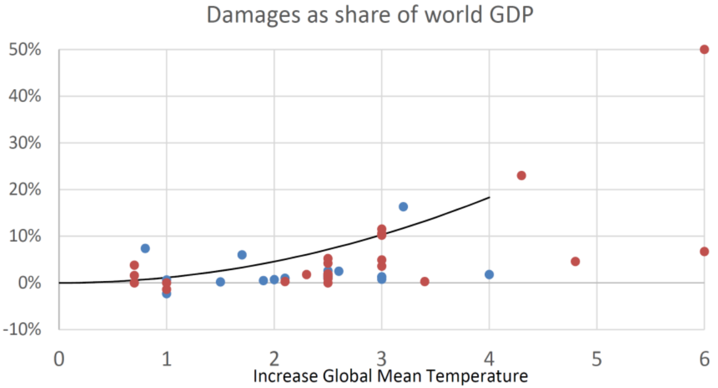


Figure: Metastudie H&S Red dots are non-duplicate studies and line is prefered regression.

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 (2012).
- 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.

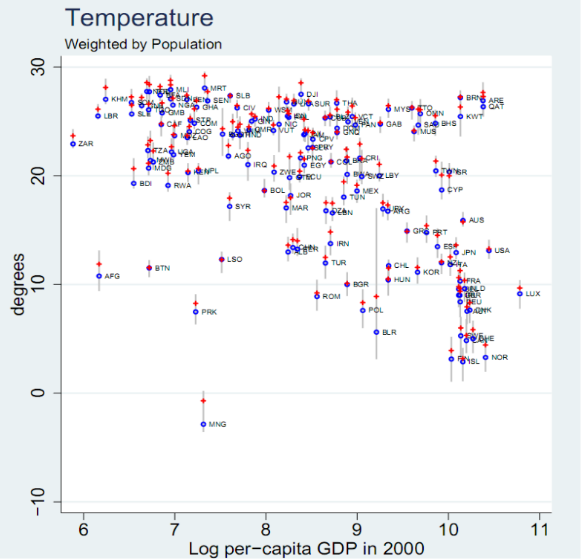


Figure: Source: Dell, Jones and Olken. American Economic Journal: Macroeconomics (2012). Blue circle (red plus) is mean temp in 1950-1959 (1996-2005). Gray lines is range of annual temperature over sample period.

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)

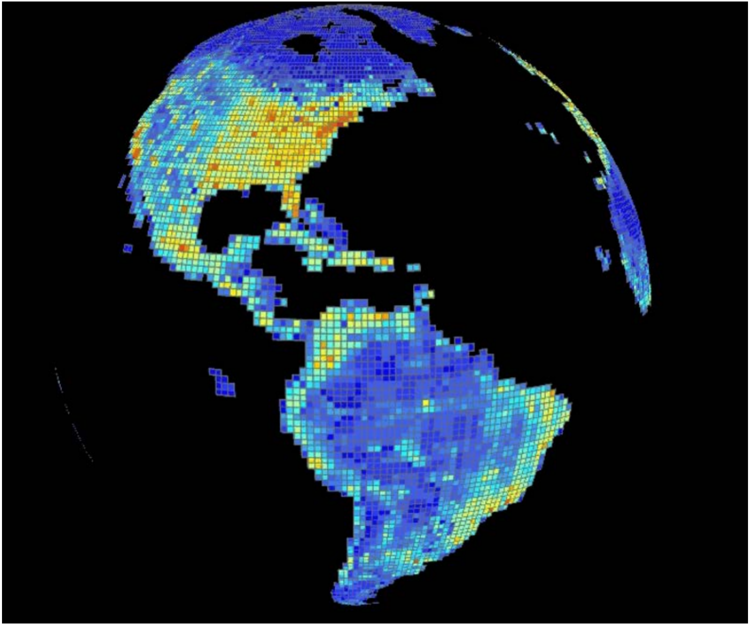
- Panel estimate (174 countries, 1960-2014) of

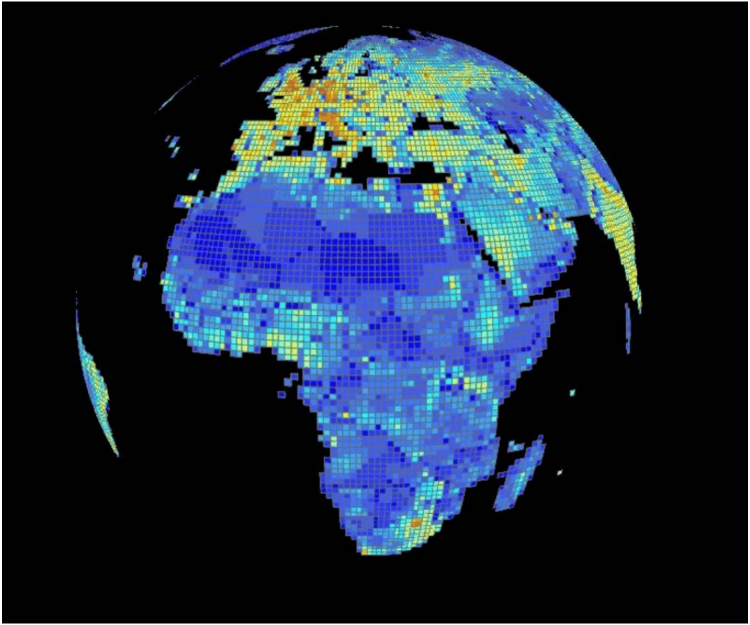
$$\Delta y_{i,t} = a_i + \sum_{l=1}^{p} \varphi_l \Delta y_{i,t-l} + \sum_{l=0}^{p} \beta_l^{+} \Delta \left(T_{i,t-l} - \bar{T}_{i,t-l} \right)^{+} + \sum_{l=0}^{p} \beta_l^{-} \Delta \left(T_{i,t-l} - \bar{T}_{i,t-l} \right)^{-} + \varepsilon_{i,t},$$

  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

- An alternative to using temporal variation as a natural expriment is to use geographic variation.
- 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!

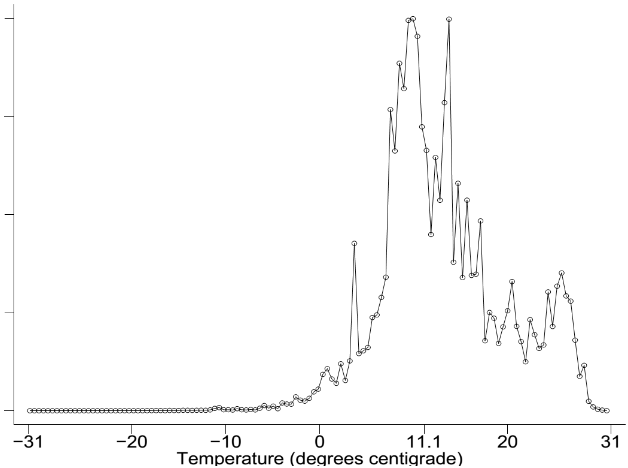




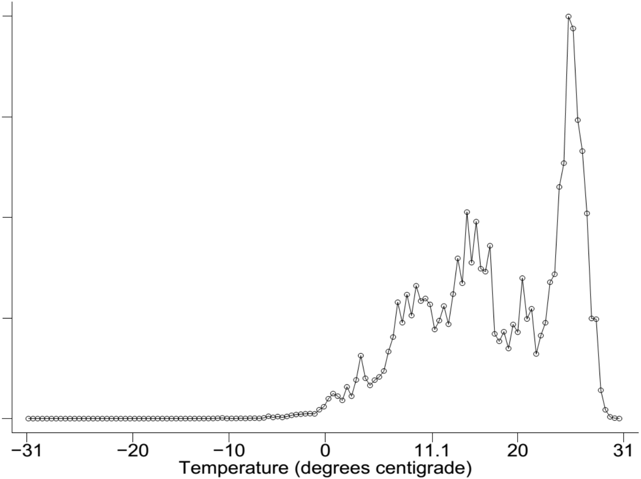
Climate data and projections

- 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.
- Benefit that long-run adaptation is taken into account. But perhaps too much. Some forms of adaptation, like mass migration might be very costly.

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 potential 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

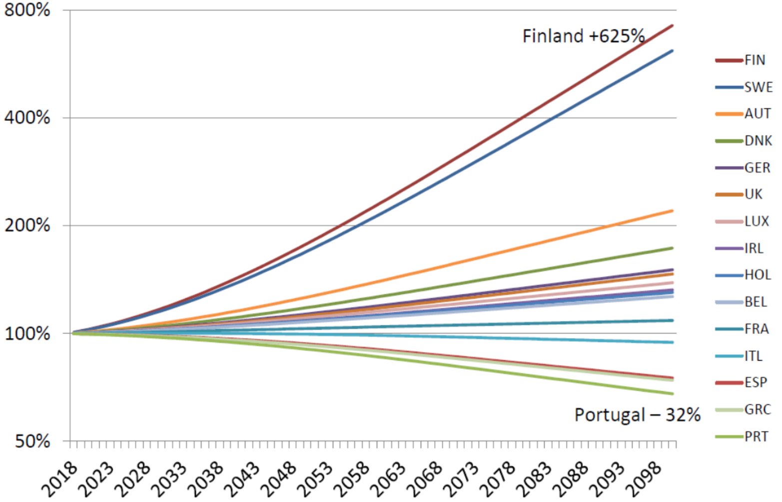


Figure: Source: Own caclulations.

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). In particular if compared to historic growth rates. But substantial uncertainty and heterogeneity.
- Very little is known for more extreme scenarios. Many of the things we should be worried about is likely not observable in data yet.
- 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 – but we need to act long before we know the consequences of climate change with certainty.