

The Climate and the Economy

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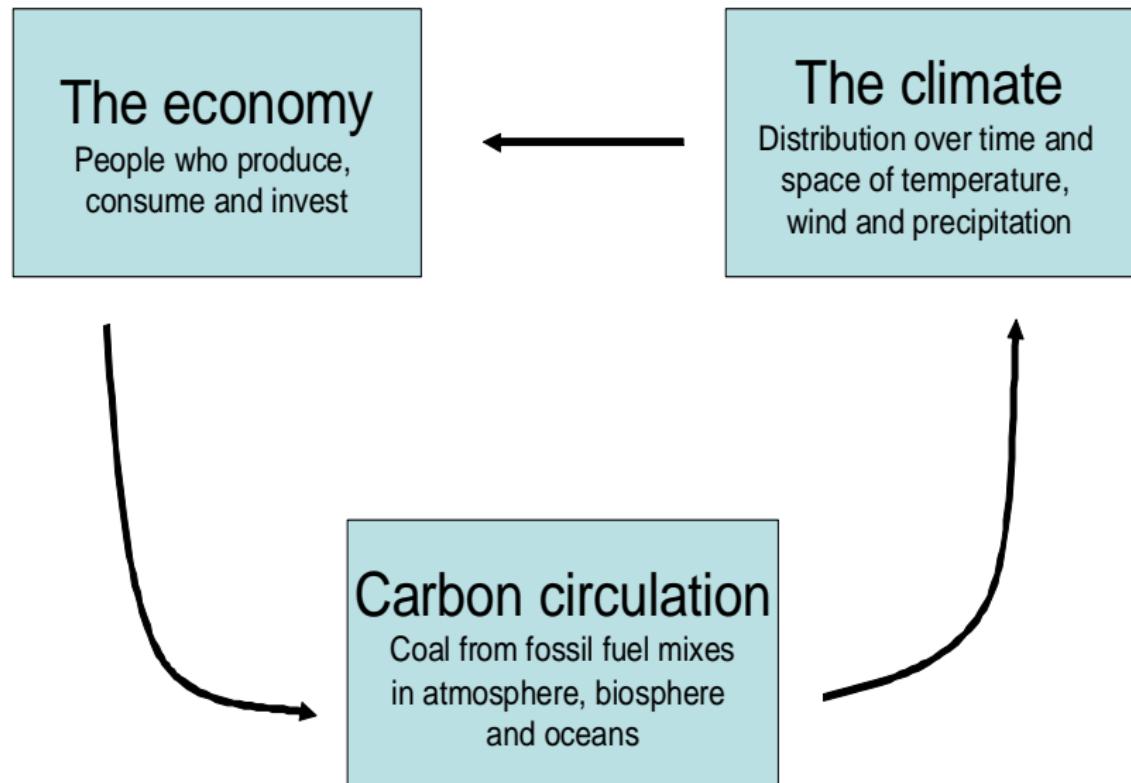
OVERVIEW

- Purpose: study models of the interaction between the global economy and the climate to
 - provide an understanding of important mechanisms and
 - analyze optimal policy.
- It involves results from both social and natural sciences.
- But we are economists – use our comparative advantage to contribute and critically analyze the economic side but take “conventional wisdom” from the natural sciences as given.
- Economics is key for analyzing effects of policy.

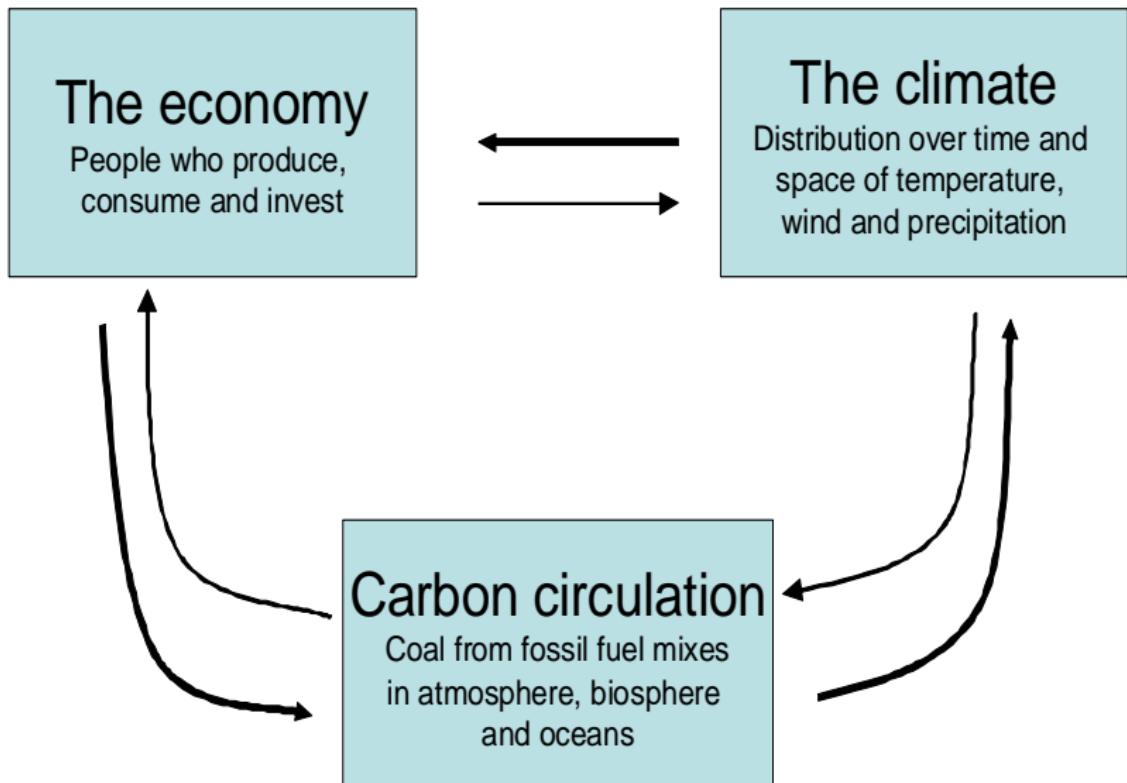
PURPOSE OF ECONOMICS HERE

- Economics is important for
 - analyzing effects of policy,
 - understanding endogenous adaptation and technical change,
 - and making forecasts.
- For all these purposes, develop IAMs: Integrated Assessment Models
- (first put together by Bill Nordhaus).

A SCHEMATIC IAM: INTERACTIONS



A SCHEMATIC IAM: DYNAMICS, BIDIRECTIONAL



TOWARD A CLIMATE MODEL

- Incoming *flow of energy*: short wave solar radiation (342 W/m² = 2400kW per football field).
- Outgoing *energy flow*, consisting of
 - direct reflection (1/3)
 - long-wave (heat) radiation (2/3)
 - where the latter is a function of, in particular, temperature and greenhouse gas concentration in earth's atmosphere.
- In a steady state, the incoming energy equals the outgoing energy. Then the earth's temperature will not change.
- What happens out of steady state? For example, without greenhouse gases and atmosphere, ground temperature would be -19. How can we understand this statement?

STEADY STATE

- A situation such that if you start there you remain there.
 - In economics we use *equilibrium* to describe what the model predicts.
 - In natural sciences they use equilibrium to describe what economists call *Steady States, a stationary situation*.
- A bath tub where the amount of water going in is the same as the amount of water going out (both evaporation and sink)/
- In an economy, a steady state involves investment equating the amount of capital depreciated and the distribution of income remaining constant.

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FORCING AND THE ENERGY BUDGET

- Consider a system (e.g., the earth) in a situation of net energy flow
 $= \text{incoming flow} - \text{outgoing flow} = 0$.
- In such a case, the *energy budget is balanced* and no heat is accumulated or lost (i.e. the temperature is in steady state).
- Suppose now that the energy budget is perturbed by a permanent positive amount F , called *forcing* (inflow increased and/or outflow decreased).
- Now the budget is no longer balanced but in surplus and the system would no longer be in steady state.

FORCING AND THE ENERGY BUDGET II

- This leads to an accumulation of heat in the system, so the temperature rises in the system, faster the larger is the energy budget surplus.
- The speed of the temperature increase also depends on heat capacity of the system (mass and material).
 - E.g., compare a balloon filled with air and a balloon filled with water.
- A new balance (steady state) will be achieved.
 - It will require that there is an additional outflow that equals F (the forcing).
 - It will take time.
- As the temperature goes up, outgoing flow increases with higher temperature (sometimes called *Planck feedback*).

A NEW BALANCE IS ACHIEVED: ENERGY BUDGET FORMALLY

- Initial change in energy budget is F (forcing).
- As long as there is a surplus in the budget, temperature increases.
- Approximate outflow (in addition to the initial balance) is proportional (with constant κ) to temperature (above the initial temperature): the increase in outflow is then $\kappa T(t)$.
- Net energy budget is then $[F - \kappa T(t)]$ (note that $T(0) = 0$, so initially the budget has a surplus of F).
- Approximate the behavior of temperature by assuming that its rate of change is proportional (with constant σ) to surplus in budget:

$$\frac{dT(t)}{dt} = \sigma (F - \kappa T(t)).$$

- Will \exists a new steady state (constant temperature)? Yes $T(\infty) = \frac{F}{\kappa}$.
- If earth were a “blackbody” without atmosphere with a temperature of 15° Celsius, $\kappa \approx 3.3 \frac{W/m^2}{K}$. Due to feedbacks is likely smaller.

FEEDBACK EFFECTS

- Gross flows are very large relative to direct effect.
- They may create feedback effects. Example, more CO₂ increases forcing, leads to
 - higher concentration of water vapor, increases greenhouse effect;
 - melting of icecaps and hence decreased direct surface reflection (albedo); and
 - changed cloud formation, changes back radiation and reflection.
- Feedback mechanisms are very important and have been so historically.
- The direct effect of CO₂ emission on temperature is quite certain. Not the case for feedback.

INCORPORATING FEEDBACKS INTO THE ENERGY BUDGET

- Let us formalize feedback as follows: increased temperature increases *effective forcing*, adding a term $xT(t)$ to the energy budget, delivering

$$\frac{dT(t)}{dt} = \sigma(F + xT(t) - \kappa T(t)) = \sigma(F - (\kappa - x) T(t)).$$

- The steady state for a given forcing F now becomes

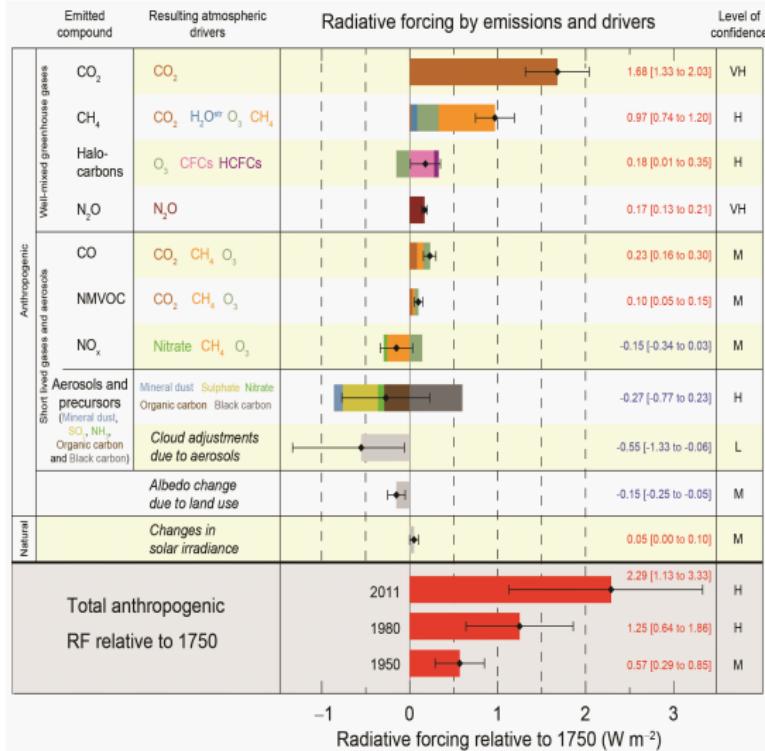
$$T(\infty) = \frac{1}{\kappa - x} F.$$

- A realistic value of $\frac{1}{\kappa-x}$ is around 0.8, but here there is large uncertainty. Recall that without the feedback effect ($x = 0$), $\frac{1}{\kappa} = 0.3$.

FORCING: WHAT ARE ITS ORIGINS (IN THIS CASE)?

- Most of the long-wave surface radiation is absorbed by clouds and greenhouse gases and re-emitted back.
- Strength depends on greenhouse gas concentration.
- Most important among greenhouse gases: water vapor. Second in importance: CO₂.
- Human activities have increased concentration of CO₂ (by burning fossil fuel) and other greenhouse gases, e.g., methane.
- Increase is equivalent to increased incoming radiation (forcing) of 1.7 and 1 W/m², respectively.

FORCING IN 2011 RELATIVE TO 1750



Source: IPCC, Assessment report 5, Summary for policy makers, fig 5.

GREENHOUSE EFFECT AND CLIMATE SENSITIVITY I

- Higher concentration of CO₂ in the atmosphere reduces outgoing energy flow (long-wave/heat radiation).
- Well approximated by a logarithmic function (Arrhenius greenhouse law, 1896). For a given concentration S of CO₂ in the atmosphere and the pre-industrial level S_0 , forcing from S is roughly

$$F(S) = \frac{\eta}{\ln 2} \ln \left(\frac{S}{S_0} \right)$$

- An often used approximation of η is 3.7.

GREENHOUSE EFFECT AND CLIMATE SENSITIVITY II

- Combine with $T(\infty) = \frac{F}{\kappa - x}$ gives

$$T(\infty) = \frac{\eta}{\kappa - x} \frac{1}{\ln 2} \ln \left(\frac{S}{S_0} \right).$$

- The ratio $\eta / (\kappa - x)$ has a very important interpretation and is often labelled the *Equilibrium Climate Sensitivity (ECS)*.
- Intergovernmental Panel on Climate Change (IPCC): ECS is “likely in the range 1.5 to 4.5°C”, “extremely unlikely less than 1°C”, and “very unlikely greater than 6°C”.
- Key issue is what will be the eventual value at which S will settle.
- As of now, it is continually increasing.

HEATING OF OCEANS

- The equation $\frac{dT(t)}{dt} = \sigma [F - (\kappa - x) T(t)]$ does not take into account heating of oceans/atmosphere separately.
- Therefore, let us introduce two new terms into energy budget for atmosphere, which *are only zero in steady state*.
- New law of motion for atmosphere:

$$\frac{dT(t)}{dt} = \sigma_1 \left[F(t) - (\kappa - x) T(t) - \sigma_2 (T(t) - T^L(t)) \right]$$

where $T(t)$ and $T^L(t)$, respectively, denote the atmospheric and ocean temperatures in period t .

HEATING OF OCEANS II

- Complete by setting

$$\frac{dT^L(t)}{dt} = \sigma_3 [T(t) - T^L(t)].$$

- Heating slows down, but is the same in the long run ($T(\infty) = T^L(\infty)$).
- One can (climate scientists do) use even more layers.

SIMULATION

- Now make a discrete-time approximation. Yields a system of difference equations:

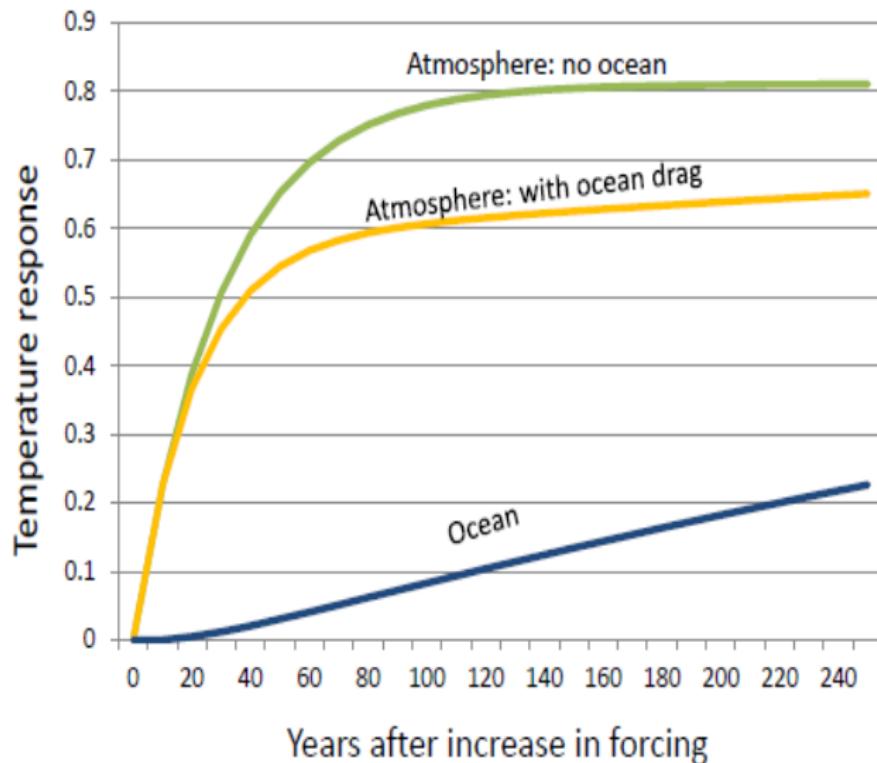
$$\begin{aligned}T_t &= T_{t-1} + \sigma_1 \left[F_{t-1} - (\kappa - x) T_{t-1} - \sigma_2 (T_{t-1} - T_{t-1}^L) \right] \\T_t^L &= T_{t-1}^L + \sigma_3 (T_{t-1} - T_{t-1}^L)\end{aligned}$$

instead of

$$\begin{aligned}\frac{dT_t}{dt} &= \sigma_1 \left[F_t - (\kappa - x) T_t - \sigma_2 (T_t - T_t^L) \right] \\ \frac{dT_t^L}{dt} &= \sigma_3 (T_t - T_t^L)\end{aligned}$$

- Can easily be simulated in a spread-sheet program. Let us look at an example.

SIMULATION: AN EXAMPLE

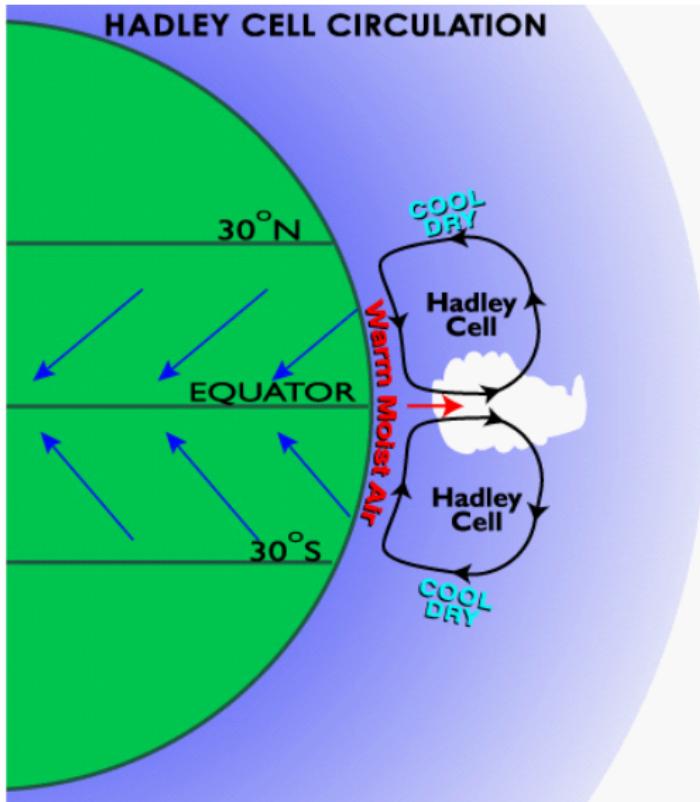


Simulation of an increase in atmospheric and ocean temperature after a permanent forcing of $1W/m^2$.

MORE ON CLIMATE MODELS IN PRACTICE

- Models of climate *around the world*.
- Circulation models (of water, air).
- Energy is not evenly radiated to the earth. Highest around equator.
- Creates systematic flows of air and water.
- Used to forecast weather, but also climate.

CIRCULATION CELLS

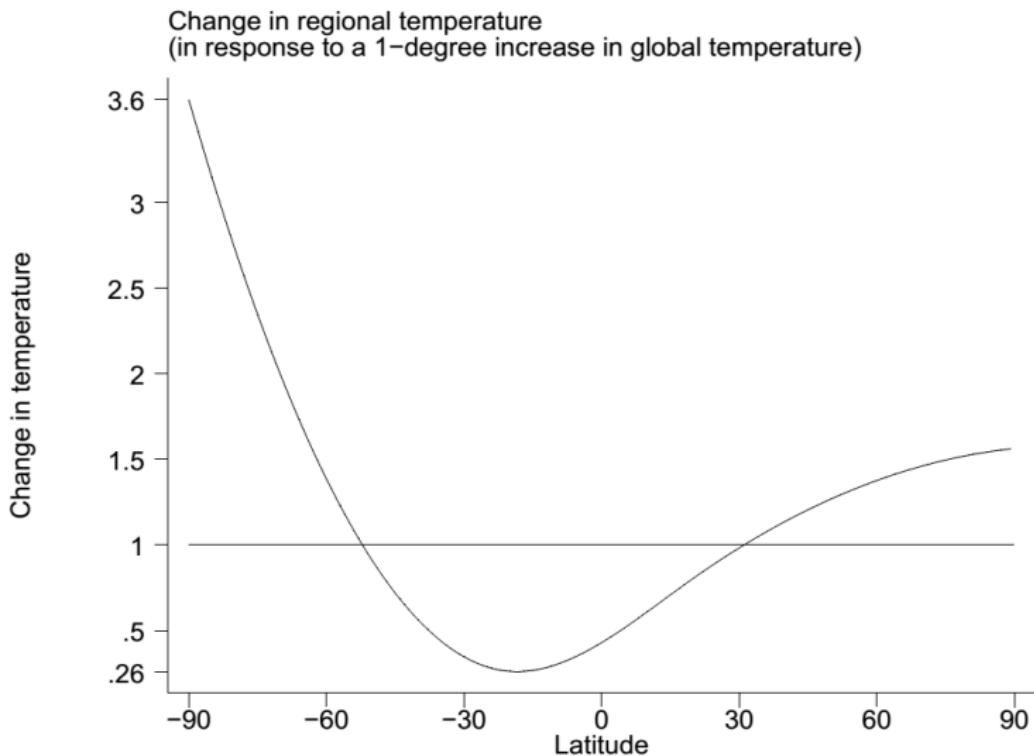


CLIMATE MODELS: KEY POINTS

- Ocean currents also transport heat from equator towards poles.
- More accurate descriptions need to model land masses and mountains.
- Climate models build on deterministic laws of physics but are chaotic in nature. This implies:
 - A “butterfly effect”: small variation in initial state, e.g., its distribution of energy, leads to unsystematic and large differences in weather a few weeks later.
 - But unconditional distribution is stable, e.g., mean and variance of temperature and wind speeds.
 - Best forecast for forecasts beyond a few weeks is unconditional distribution.
- State-of-the-art climate models are built on these principles.

DOWNSCALING (PATTERN SCALING)

- Circulation models are (very) large and (very) time-consuming to run.
- Simplification: use a statistical representation of how a change in global mean temperature affects different locations.
- Simplest case: use latitude. Estimate a different sensitivity β_i for each latitude.
- $T_{i,t} = \bar{T}_i + \beta_i * T_t + z_{i,t}$



THE HISTORIC CLIMATE

- Use various proxy data for temperature, e.g., tree rings, corals, plankton, pollen...
- Also data on historic greenhouse gas concentrations, trapped in ice.
- Positive correlation, with concentrations lagging temperature, suggesting positive feedback.

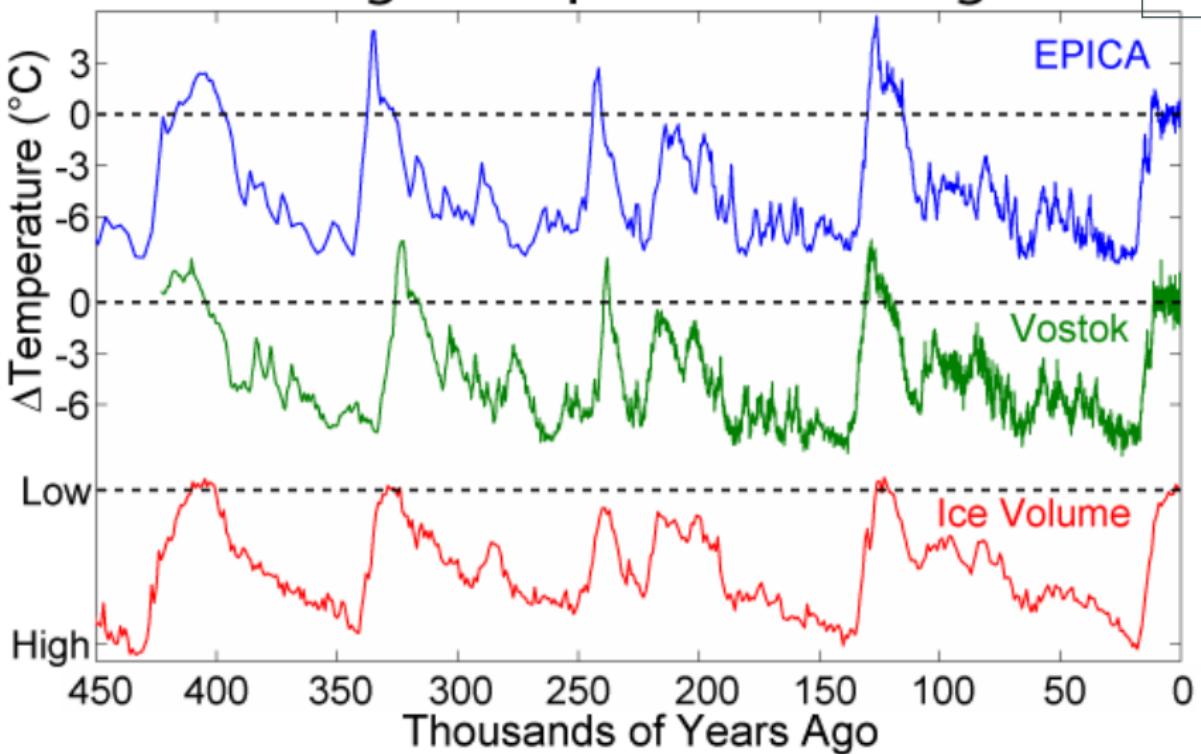
ICE AGES

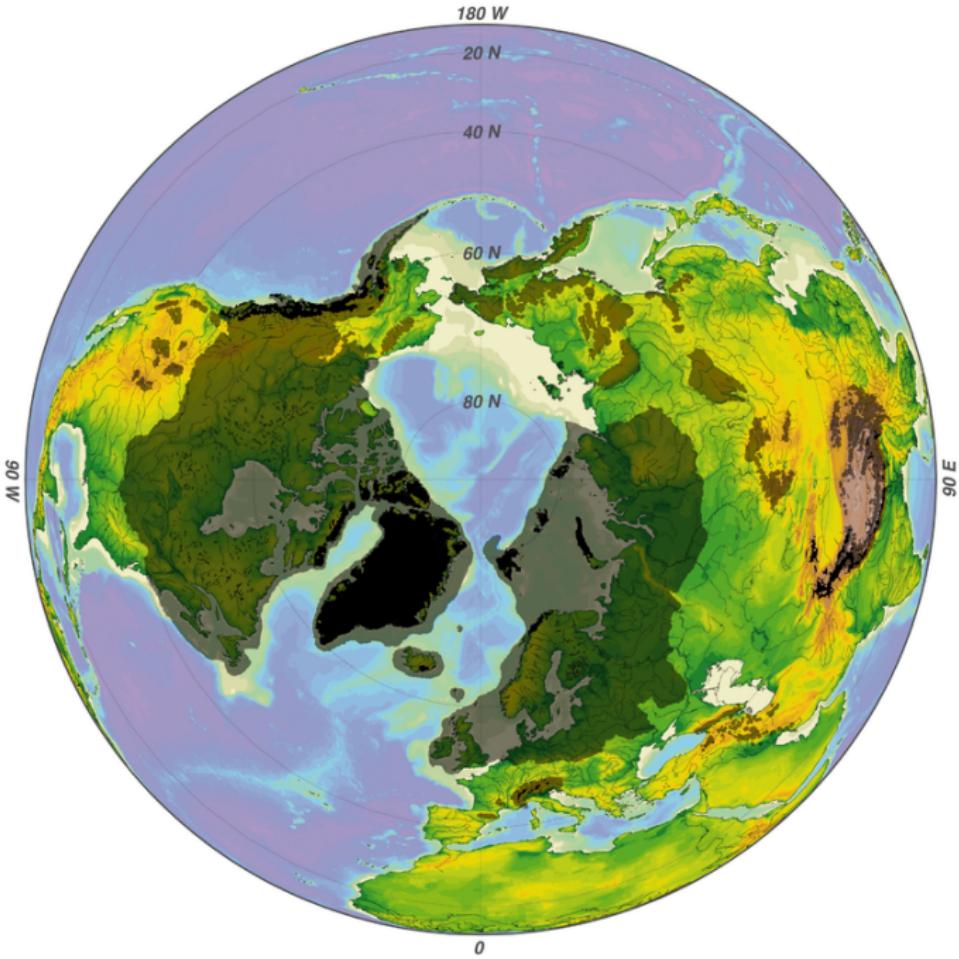
- Ice ages are much longer than interglacial periods.
- About 100,000 years between each interglacial period.
- Small changes in solar influx get amplified by feed-back.
- A key mechanism may be ice-albedo feedback (Arrhenius).
- A small negative F leads to a build-up of the icecap.
- An increased albedo of the earth amplifies the initial effect.
- Additional effects may come from greenhouse gases.
- For more recent climate info, see



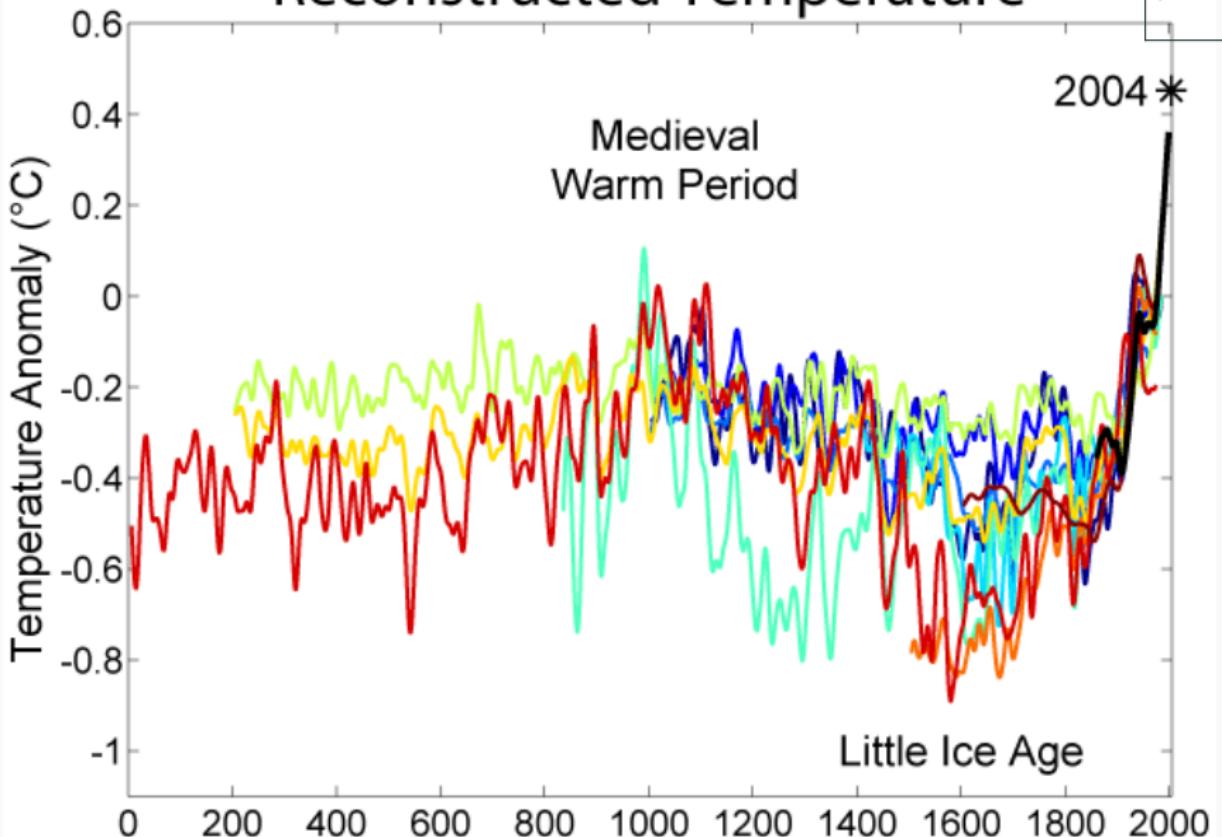
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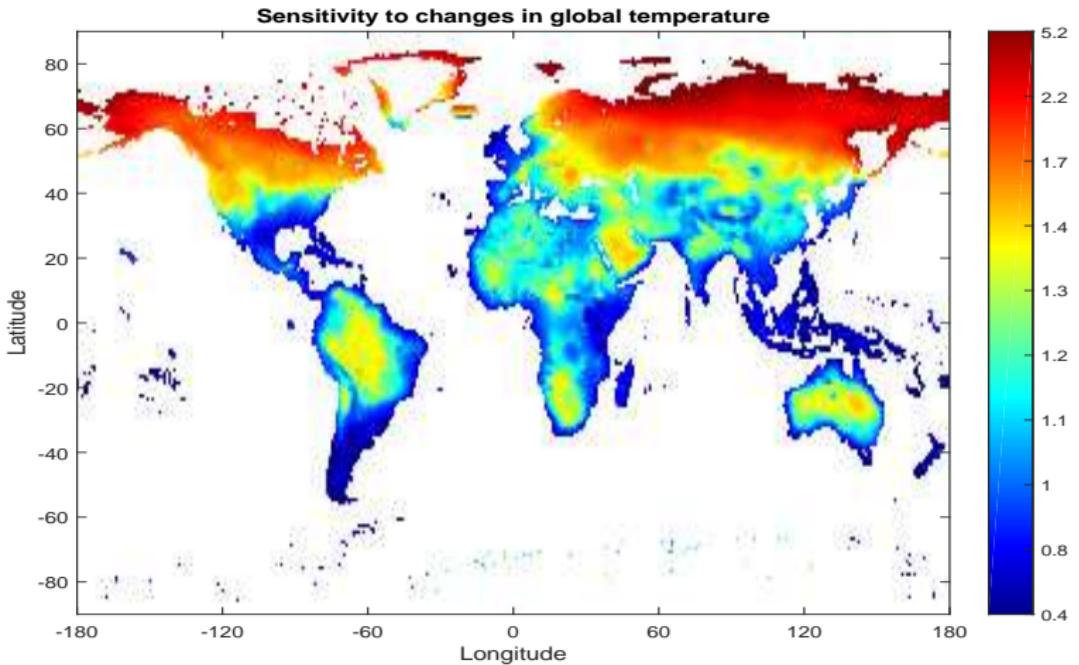
Ice Age Temperature Changes





Reconstructed Temperature





NON-LINEARITIES

- Recall that the equilibrium climate sensitivity is affected by feedbacks

$$T(F) = \frac{\eta}{\kappa - x \ln 2} \ln \left(\frac{S}{\bar{S}} \right).$$

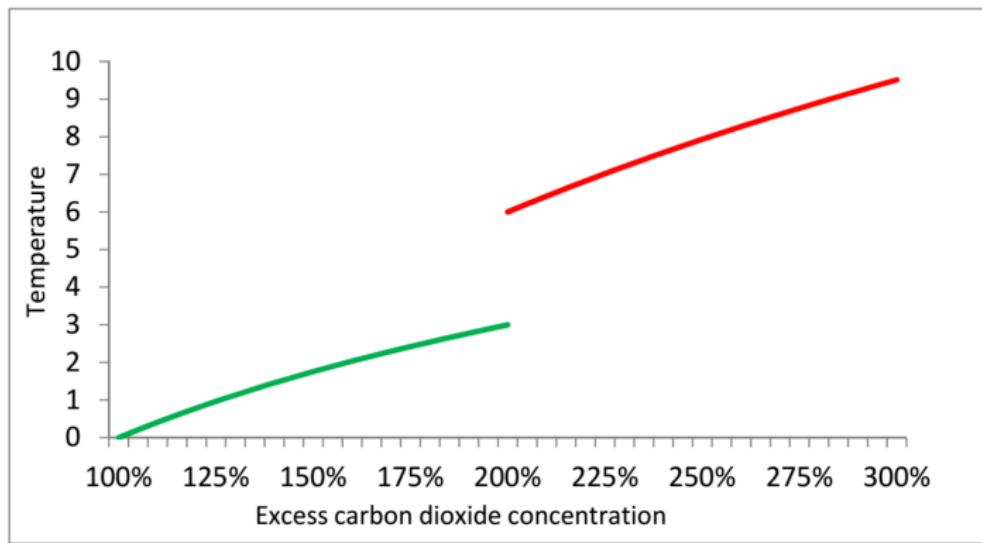
- We are quite uncertain about the value of x .
- One thing that could happen is that it suddenly increases at some temperature. For example, suppose

$$x = \begin{cases} 2.1 & \text{if } T < 3^\circ C \\ 2.72 & \text{else} \end{cases}$$

- This produces a jump in the relation between CO₂ and long-run temperature.

Tipping points

- Suppose $\eta = 3.7$ and $\kappa = 3.3$. and $x = 2.1$ if $T < 3^\circ C$ and 2.72 else. Then, the relation between CO₂ concentration and long-run temperature looks like follows



TIPPING POINTS:2

- Tipping points like then one described are possibilities and many of them are known to exist on local and regional scales.
- If they exist on a global scale and if so at which temperatures is much more debated.

FEEDBACK UNCERTAINTY

- Uncertainty in the feedback produces a skewed distribution of the climate sensitivity.
- Since $\lambda \equiv \frac{\eta}{\kappa-x}$ is a non-linear transformation of x , uncertainty about λ becomes very skewed with possibilities of very large values.
- Suppose the uncertainty about x by a symmetric triangular density function with mode 2.1 and endpoints at 1.35 and 2.85. The mean, and most likely, value of x translates into a climate sensitivity of 3.

Feedback uncertainty

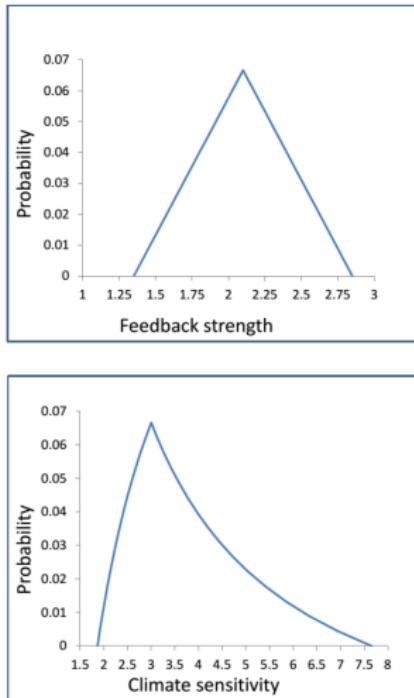


Figure: Example of symmetric uncertainty of feedbacks producing right skewed climate sensitivity.

The carbon cycle

THE CARBON CYCLE

- The burning of fossil fuel (coal, oil, natural gas) leads to CO₂ emissions into the atmosphere, which (as we have seen) leads to significant warming, at least in most of the probabilistic distribution of outcomes.
- Warming is potentially damaging to our economies—and we will look at damage measurements later—and if so the burning of fossil fuel is a negative externality. There is need for government action.
- For policy analysis as well as for forecasts, we need to know the dynamic mapping from path of emissions to path of CO₂ concentrations.

TWO MODELING ALTERNATIVES

- We will mainly look at two approaches:
 - ➊ Stock-flow approach. Idea: different interacting reservoirs of carbon, with a continuous flow between these. A stable system always tending towards a steady state.
 - ➋ Non-structural (reduced form): define a depreciation function that specifies how much of an emitted unit remains in the atmosphere over time. Can be specified rather generally, but we look at a simple form.
- We will also look at a formulation which blends the carbon cycle with a climate model directly: the CCR (carbon-climate response).

EASY STOCK-FLOW CASE IN CONTINUOUS TIME

- Assume 2 reservoirs S and S^L . $S(t)$ represents the atmospheric carbon concentration in period t and $S^L(t)$ represents that in the deep oceans.
- Flows from S to S^L : proportional to S , with proportionality factor ϕ_1 .
- Flow in other direction proportional to S^L , with proportionality factor ϕ_2 .

Changes in stocks equal net flows (in minus out), apart from emission inflow E . This gives

$$\begin{aligned}\frac{dS(t)}{dt} &= -\phi_1 S(t) + \phi_2 S^L(t) + E(t) \\ \frac{dS^L(t)}{dt} &= -\phi_2 S^L(t) + \phi_1 S(t).\end{aligned}$$

With $E(t) = 0$, steady state satisfies

$$\begin{aligned}0 &= -\phi_1 S + \phi_2 S^L \\ 0 &= \phi_1 S - \phi_2 S^L\end{aligned}$$

which cannot be uniquely solved: all solutions satisfy $S = \frac{\phi_2}{\phi_1} S^L$. Why?
 Note that $S(t) + S^L(t) = \int_{s=0}^t E(s) ds$ at all times. The total amount of carbon increases as emissions continue.

SAME CASE WITH DISCRETE-TIME APPROXIMATION

$$S_t - S_{t-1} = -\phi_1 S_{t-1} + \phi_2 S_{t-1}^L + E_{t-1}.$$

$$S_t^L - S_{t-1}^L = \phi_1 S_{t-1} - \phi_2 S_{t-1}^L$$

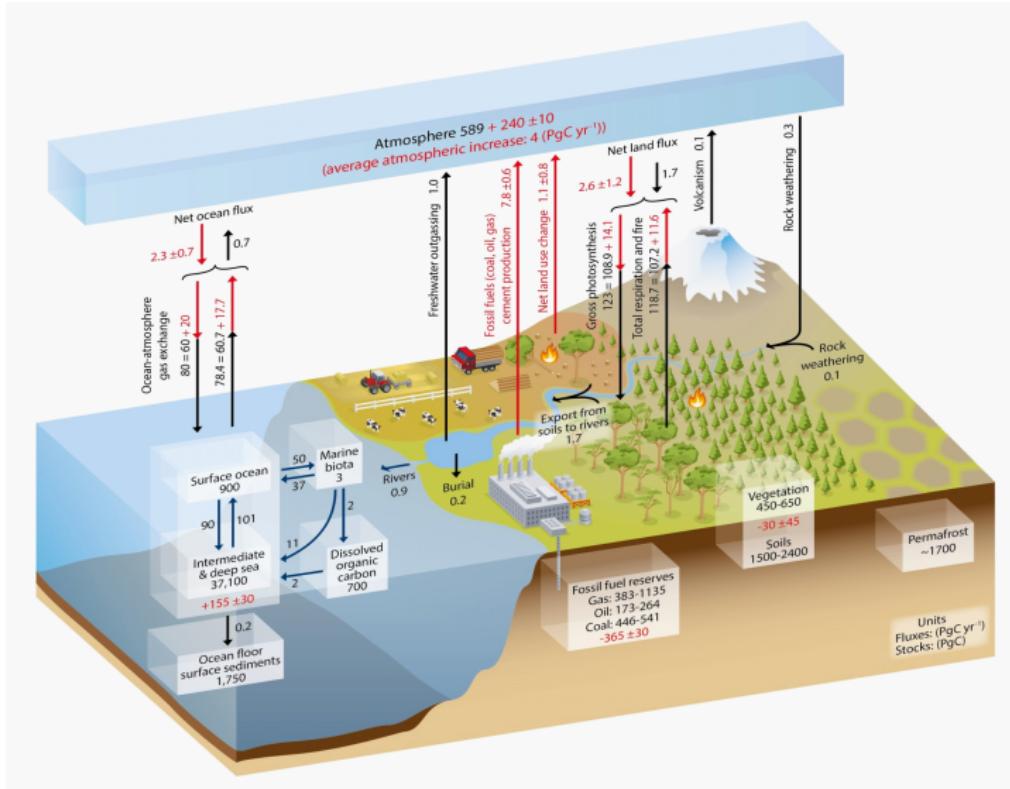
- Same steady state and approximately the same dynamics.
- Linear systems (in discrete or continuous time) can be solved analytically.
- Suppose emissions stop at t . Then deviation from steady state $S_t = \frac{\phi_{21}}{\phi_{12}} S^L$ vanishes over time as determined by the factor

$$(1 - \phi_1 - \phi_2)^{t+s}$$

- The law of motion for the stocks follows ($s \geq 0$)

$$S_{t+s} = \frac{\phi_2}{\phi_1 + \phi_2} (S_t + S_t^L) - \frac{\phi_2 S_t^L - \phi_1 S_t}{\phi_1 + \phi_2} (1 - \phi_1 - \phi_2)^s$$
$$S_{t+s}^L = \frac{\phi_1}{\phi_1 + \phi_2} (S_t + S_t^L) + \frac{\phi_2 S_t^L - \phi_1 S_t}{\phi_1 + \phi_2} (1 - \phi_1 - \phi_2)^s.$$

THE STOCK-FLOW APPROACH VISUALLY



Global carbon cycle. Stocks in GtC (PgC) and flows GtC/year. Source: Intergovernmental Panel on Climate Change (IPCC) (2013), Figure 6.1.

A MORE GENERAL STOCK-FLOW MODEL: THREE RESERVOIRS

- S_t represents (carbon concentration in) the atmosphere in period t , S_t^U the surface ocean, and finally S_t^L the deep oceans.
- Flows still assumed to be proportional to stocks and change in a reservoir is equal to net flow into it.
- We then have

$$S_t - S_{t-1} = -\phi_{12}S_{t-1} + \phi_{21}S_{t-1}^U + E_{t-1}$$

$$S_t^U - S_{t-1}^U = \phi_{12}S_{t-1} - (\phi_{21} + \phi_{23})S_{t-1}^U + \phi_{32}S_{t-1}^L$$

$$S_t^L - S_{t-1}^L = \phi_{23}S_{t-1}^U - \phi_{32}S_{t-1}^L.$$

CALIBRATION

- Two alternative ways to go.
 - Choose the parameters to make model dynamics match the dynamics of much more complicated carbon-cycle models as closely as possible.
 - Take linear model seriously and use measured flows.
- Let's use the pre-industrial flows and stocks for the calibration.
 - Before industrialization we had 589 GtC in atmosphere and a flow to surface ocean of 60 GtC, implying $\phi_{12} = \frac{60}{589} \approx 0.102$.
 - The flow from the surface ocean to the atmosphere gives $\phi_{12} = \frac{60.7}{900} \approx 0.067$.
 - Use flow to deep ocean, giving $\phi_{23} = \frac{90}{900} = 0.100$.
 - Finally, the flow from the deep ocean to the surface ocean is the same, giving $\phi_{32} = \frac{90}{37100} \approx 0.00243$.

PROPERTIES OF STEADY STATE

- If emissions stop, this system also approaches a steady state. Solve

$$0 = -\phi_{12}S + \phi_{21}S^U$$

$$0 = \phi_{12}S - (\phi_{21} + \phi_{23})S^U + \phi_{32}S^L$$

$$0 = \phi_{23}S^U - \phi_{32}S^L.$$

- Again no unique solution, but all solutions satisfy

$$S = \frac{\phi_{21}}{\phi_{12}} \frac{\phi_{32}}{\phi_{23}} S^L$$

$$S^U = \frac{\phi_{32}}{\phi_{23}} S^L.$$

- i.e., proportions between stocks are always restored. Stocks sum to sum of past emissions.

NON-STRUCTURAL CARBON CIRCULATION MODELS

- Structural model may be too simplified. Misses non-linearities, and other relevant variables.
- Could then instead try to match key characteristics directly (IPCC and Archer 2005).
 - ① A share (ca 20-25%) stays very long (thousands of years) until CO₂ acidification has been buffered.
 - ② The remainder decays with a half-life of a few centuries.
 - ③ A share (ca 50%) of carbon emissions is removed quite quickly (a few years to a few decades).
- These features can be modeled directly by a depreciation function (rather: “remainder function”), d_s that says how much remains of an emitted unit after s period.

$$d_s = \varphi_L + (1 - \varphi_L) \varphi_0 (1 - \varphi)^s .$$

CALIBRATION

- Use decades.

$$d_s = \varphi_L + (1 - \varphi_L) \varphi_0 (1 - \varphi)^s.$$

① A share stays forever $d_\infty = .2$. So $\varphi_L = .2$

② The rest has a half life of 300 years: $(1 - \varphi)^{30} = \frac{1}{2}$.

Gives $\ln(1 - \varphi) = \frac{\ln \frac{1}{2}}{30}$, so $-\varphi \approx -0.023$.

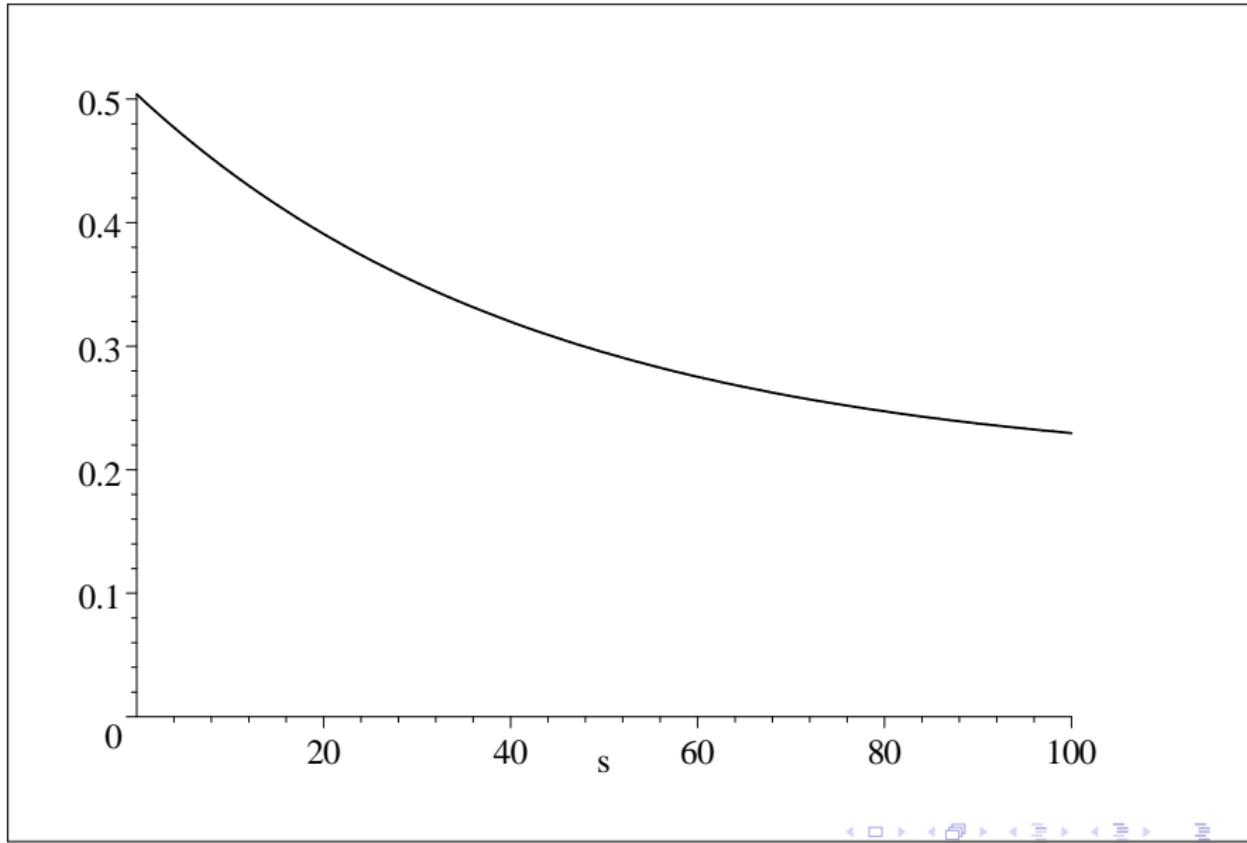
③ Half of the emissions are gone fast: $d_1 = 0.5$,

- $d_1 = 0.5 = 0.2 + (1 - 0.2) \varphi_0 (1 - 0.023)^1, \Rightarrow \varphi_0 = 0.38.$

Implies

$$d_s = [\varphi_L + (1 - \varphi_L) \varphi_0 (1 - \varphi)^s]_{\varphi_L=0.2, \varphi=0.023, \varphi_0=0.38}.$$

$$[\varphi_L + (1 - \varphi_L) \varphi_0 (1 - \varphi)^s]_{\varphi_L=0.2, \varphi=0.023, \varphi_0=0.38}$$



NON-LINEARITIES

- The parameters in the models we have presented are likely to be affected by the emission scenario: the amount and timing of emissions.
- For example, more emissions reduce the capacity of oceans to store carbon (temperature and chemistry).
- Implies that more than 20-25% stays in atmosphere for thousands of years if cumulated emissions are large.
- With 10 times current cumulated emissions, twice as big a share is likely to remain.

CCR: CARBON CLIMATE RESPONSE

- The climate system (linking S to T) and the carbon cycle (linking E to S) are dynamic and non-linear.
- An increase in forcing has a delayed impact (increasing over time) on temperature and is concave (logarithmic).
- Emission of carbon has a decaying impact (decreasing over time) on atmospheric CO₂ concentration. The relation is convex since other sinks' storage capacities decrease when emissions have been large.
- Surprisingly, these non-linearities seem to cancel each other in most advanced climate models. The global mean temperature thus becomes approximately linear in cumulative emissions.

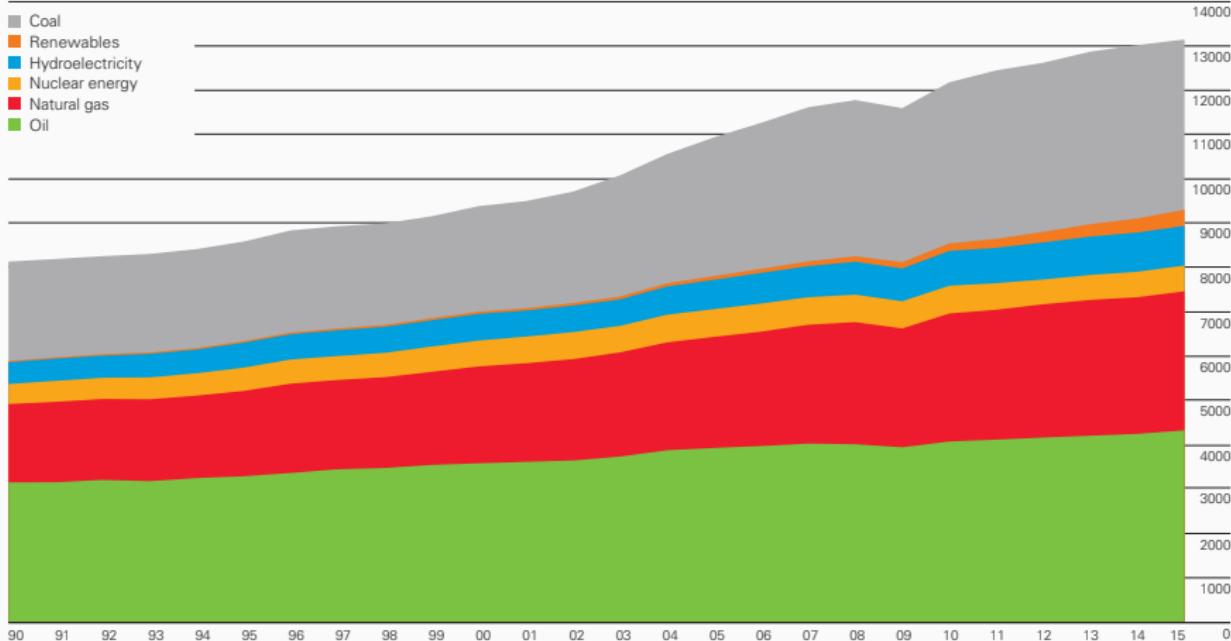
CCR: TAKING STOCK OF THE OVERALL CARBON CLIMATE RESPONSE

- Increase in GMT (global mean temperature T) is between 1 and 2.1 degrees Celsius per 1,000 GtC both in short and long run. This constant is called Carbon Climate Response (CCR).
- Note that these are emissions not net contributions to the stock of CO_2 .

World consumption

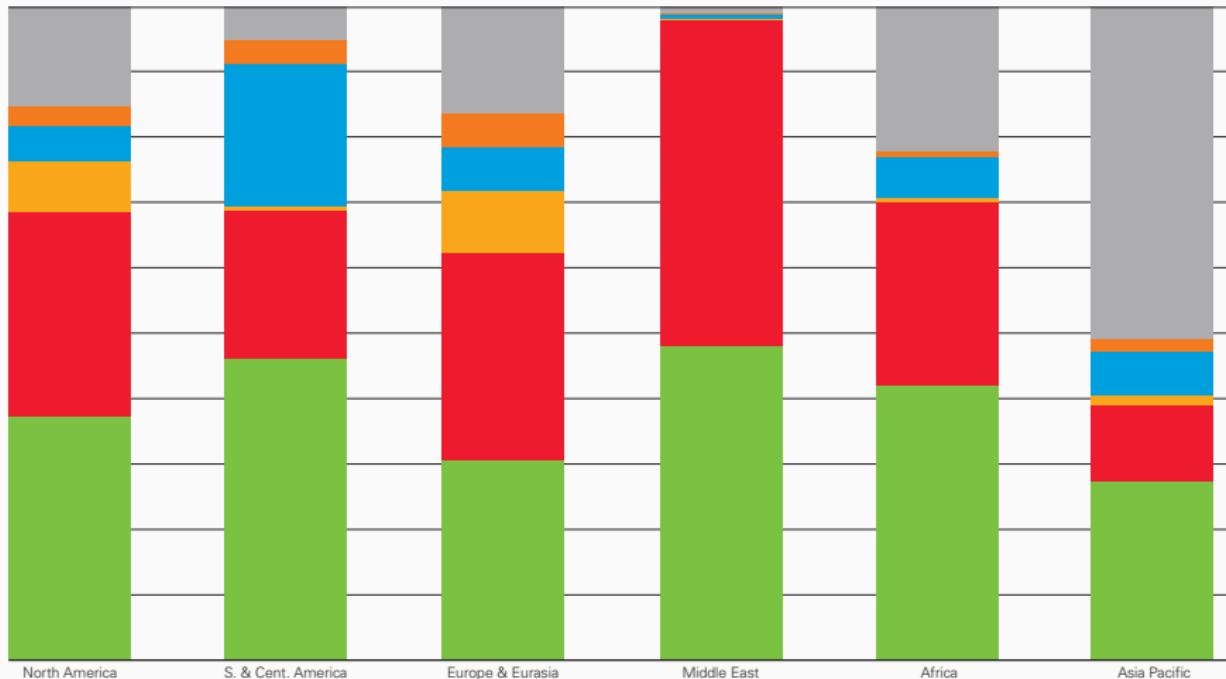
Million tonnes oil equivalent

- Coal
- Renewables
- Hydroelectricity
- Nuclear energy
- Natural gas
- Oil



Regional consumption by fuel 2015

Percentage



WHAT SIZE AND KIND OF EMISSIONS?

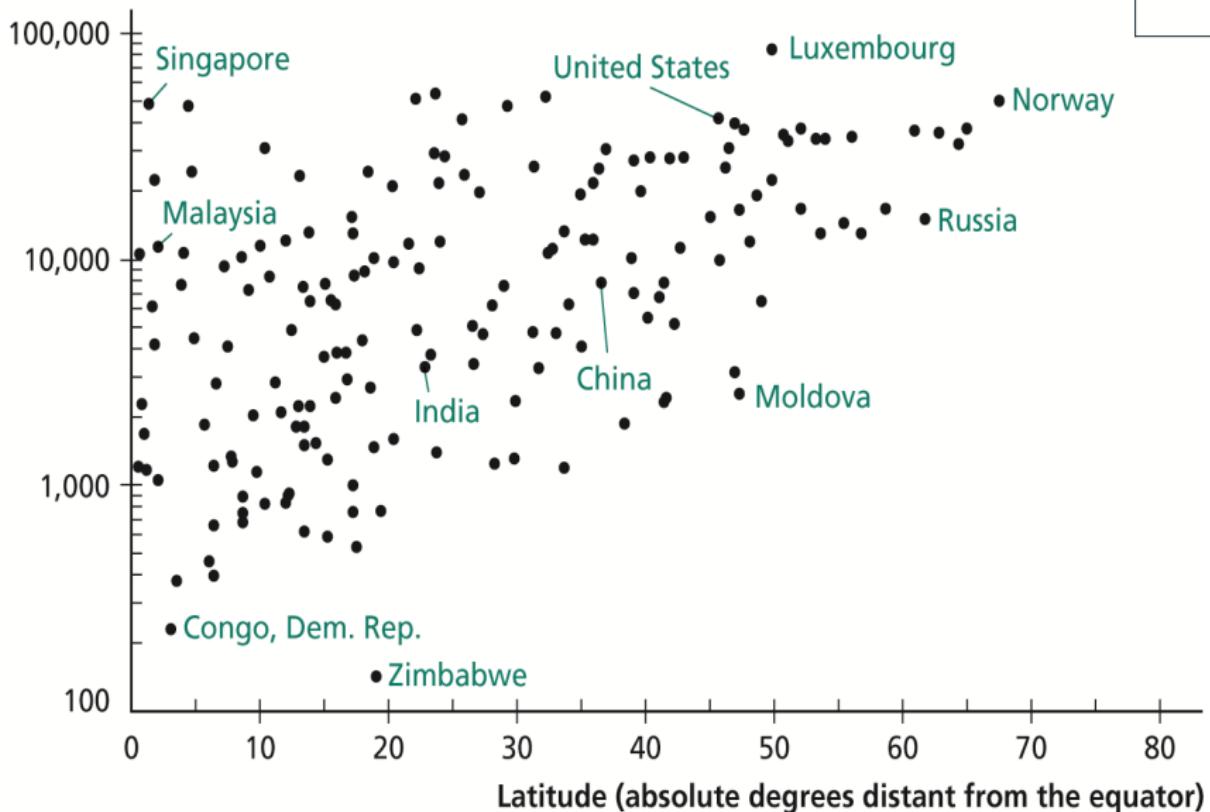
- What remains in the ground: (An assessment that depends on extracting technology, maybe more in the future)
 - Reserves of oil plus gas about 300 GtC (a bit more with fracking no more than 500).
- Coal is more than 3000 GtC,
- Coal is what really matters.
- Emissions are (now) about 10Gtc/ per year which means that about half of that is the (permanent) net increase of CO₂.

Damages

DAMAGES

- Give examples of different approaches to measuring and aggregating damages from climate change. Damages could be positive (bad) or negative (good).
- Climate change is a global phenomenon and affects the economy in a large number of ways.
- Two ways to estimate total effects:
 - bottom-up: quantify all potential effects and sum up
 - reduced form: directly use correlation between natural variation in climate and relevant aggregate outcomes (GDP, mortality, etc.).
- Approaches have different pros and cons. Complementary.

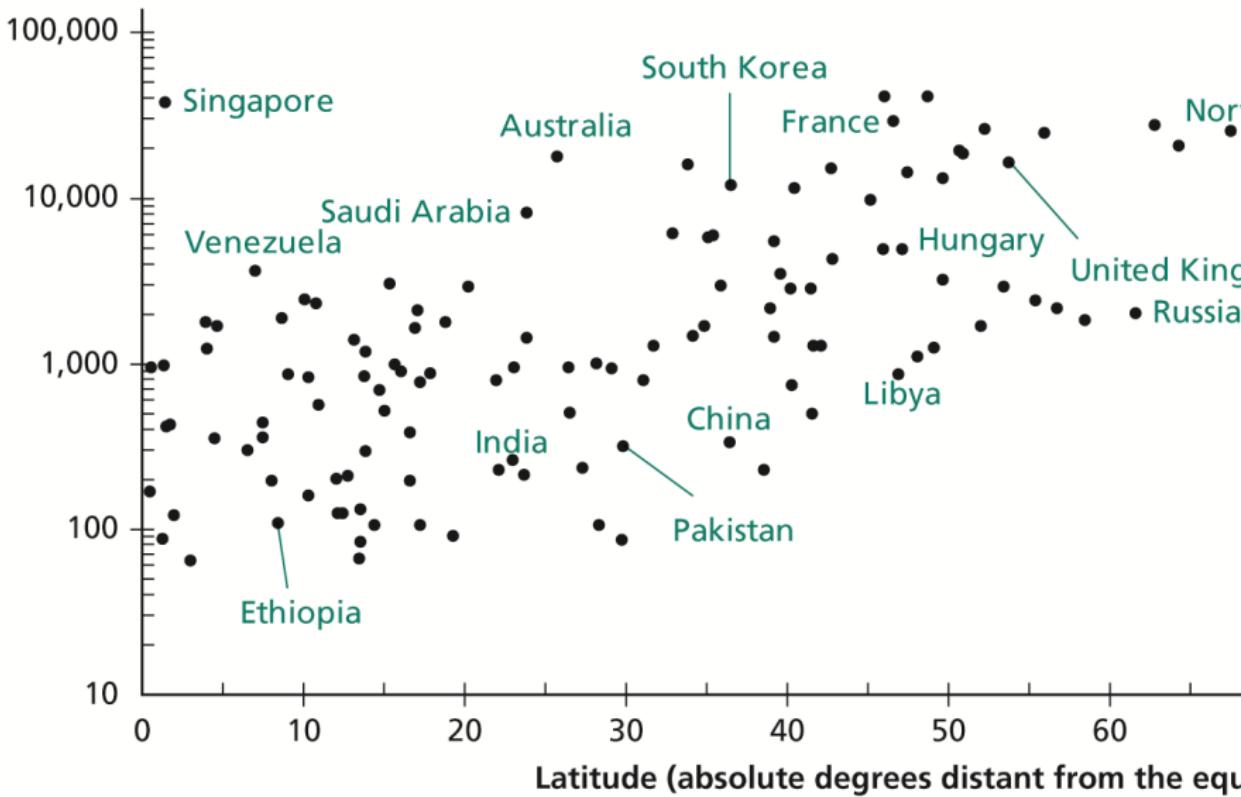
GDP per capita, 2009 (2005 Dollars, ratio scale)



LATITUDE VS. AGRICULTURAL GDP PER WORKER

/home/

Agricultural GDP per agricultural worker, 2009 (ratio scale)



NORDHAUS'S DAMAGES IN RICE: A BOTTOM-UP APPROACH

Nordhaus's DICE model (Dynamic Integrated model of Climate and the Economy) and the later RICE (also dynamic, but with R for Regional) do the bottom part as follows.

- Divide effects into: (i) agriculture, (ii) sea-level rise, (iii) other market sectors, (iv) health, (v) non-market amenity impacts, (vi) human settlements and eco-systems and (vii) catastrophes.
- Use 13 regions: U.S., OECD part of Europe, Eastern Europe, Japan, Russia, China, Africa, India, other high income, other middle, other low middle income, and low- and high-income OPEC.

FUNCTIONAL SPECIFICATION

- For each sector and region, a damage function, measuring the damage or willingness to pay for non-market items, is expressed as a % of GDP.
- Assuming damages are proportional to GDP amounts to TFP damages.
- For each region, sum over sectors.
- Add up to give a damage function per region.

- Most studied. Damage depends chiefly on CO₂, temperature, precipitation, and adaptation.
- Nordhaus summarizes various studies of effects:

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

- Positive effects if initial temperature is below 11.5 degrees. Suggests quadratic damage $\alpha_{ag}^1 (T + T_0^j) + \alpha_{ag}^2 (T + T_0^j)^2 + \alpha_{ag}^3$.

OTHER SECTORS

- Similar approach but typically fewer studies to rely on.
- Does not add up to very much for a temperature increase of 2.5 degrees. Global population-weighted values for damages at 2.5 degrees: Ag =0.17%, other market =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.

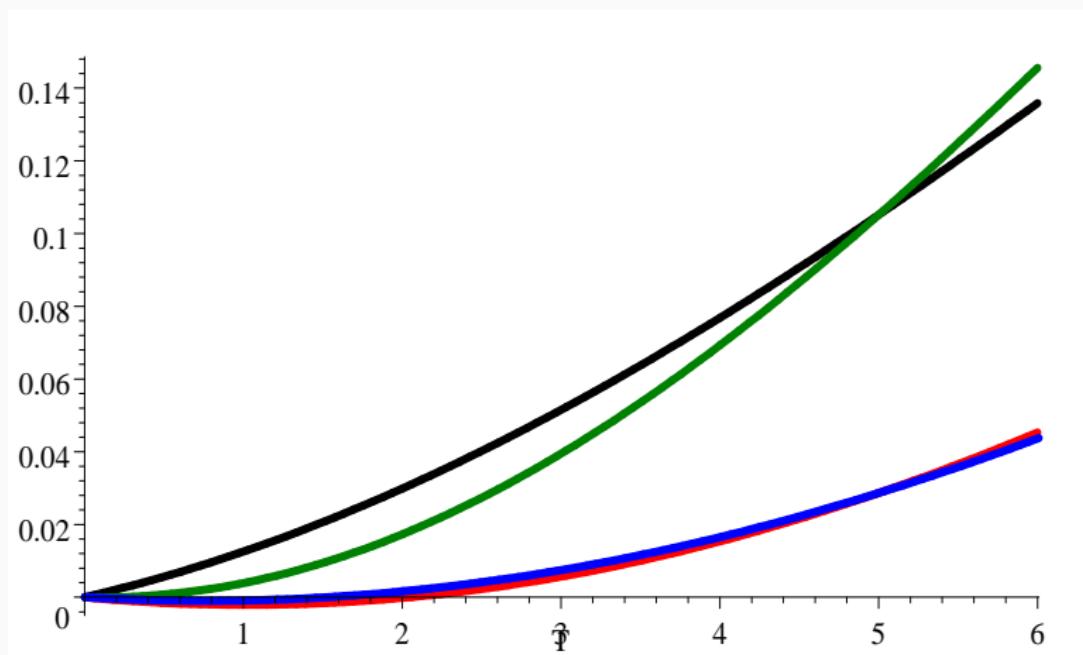
CATASTROPHES

- Survey among (mostly natural-science) experts: “What is the probability of a 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, respectively.
 - India twice as willing, the U.S. and China less than half.

NORDHAUS 2000 SUMMARY

- Damages as percent of GDP, described by

$D(T) = 1 - \frac{1}{1 + \theta_{j,1}T + \theta_{j,2}T^2}$ with region-specific θ_j s, giving
(Blue-USA, Red-Chi, Green-Eur, Black-LI).

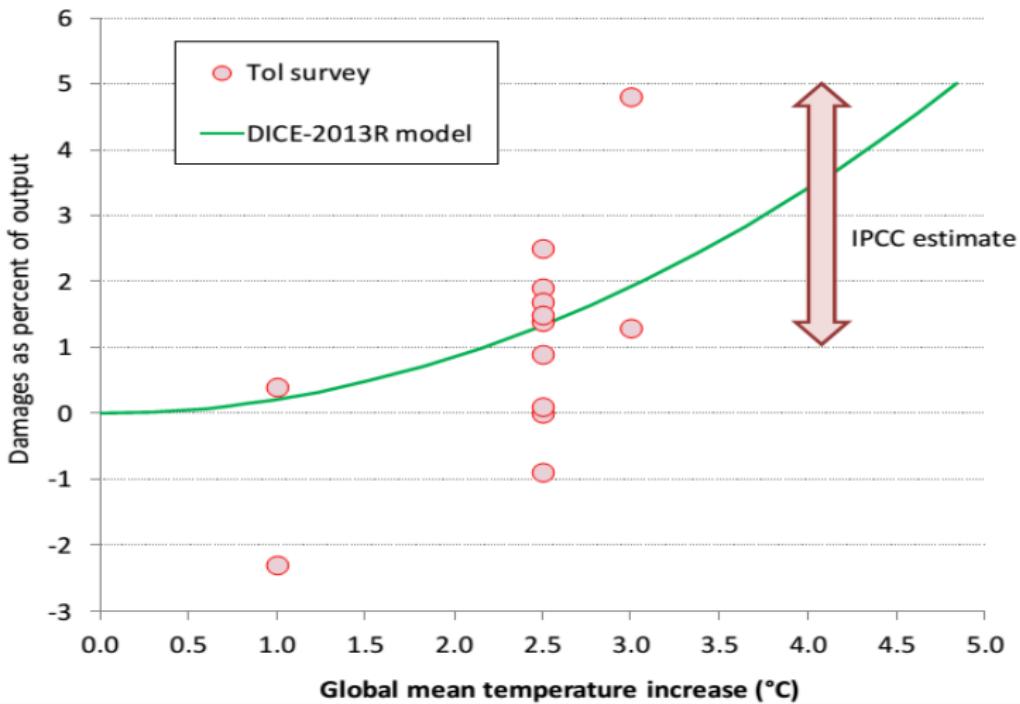


- Goes back to more ad-hoc description. Global damages

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

- Also allows a term in T^3 producing more convex damages.
- Other models have included even larger exponents on T , but without much of a motivation.
- The model FUND uses a *random exponent* from the interval 1.5-3.
- Nordhaus stresses that the damage function for high temperatures (> 3 or 4 degrees?) should not be taken very seriously.

- Another bottom-up study, but for Europe only.
- Sums the impact for 5 types of damages: agricultural production, river floods, coastal effects, tourism (market), and health.
- Uses different high-resolution models 50x50 km and uses distribution of weather outcomes (not only temperature).
- Compares 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.



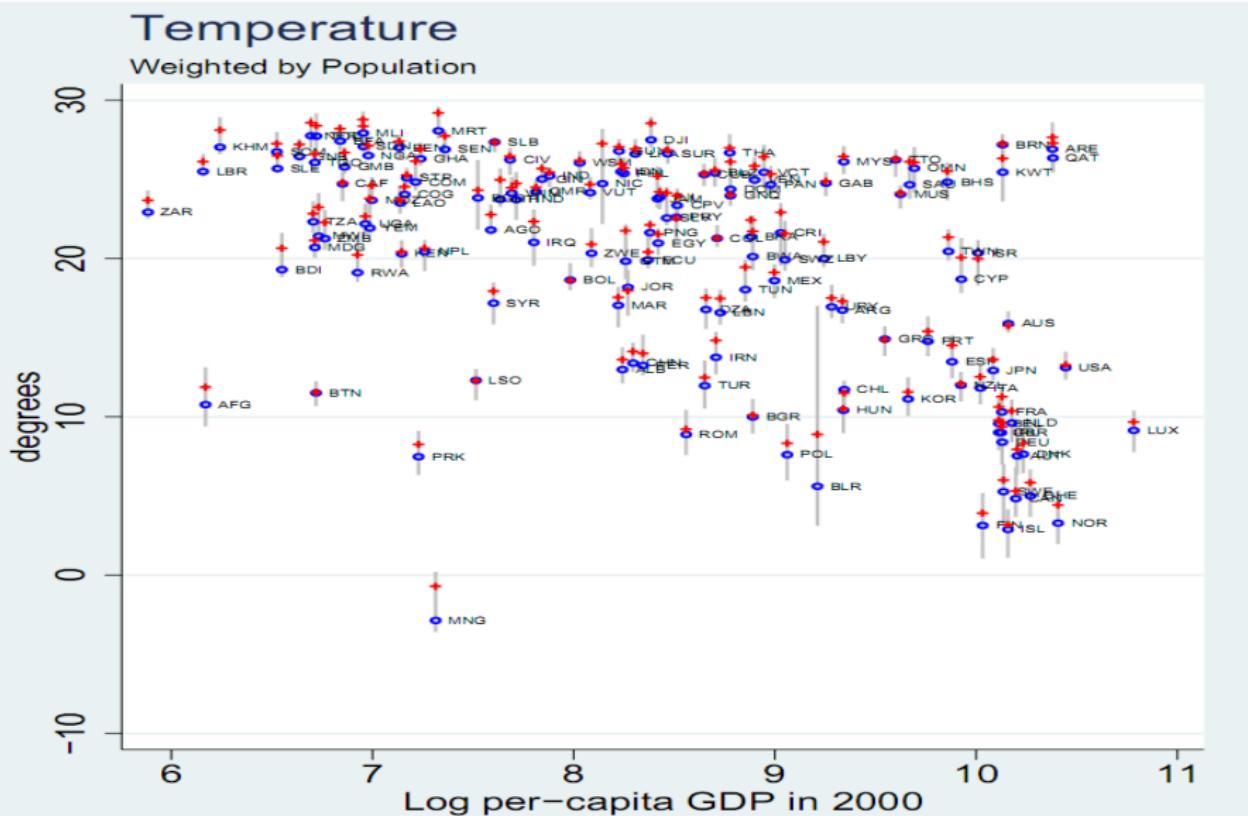
The solid line is the estimate from the DICE-2013

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

REDUCED-FORM DAMAGES

- 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," NBER Working Papers 19578 (JEL).
- Microstudies yield credible identification, and perhaps yield insights on mechanisms, but often with limited external validity and no general-equilibrium effects taken into account.
- Aggregate reduced forms can complement in this sense. One of few: Dell, Jones, and Olken. NBER WP 14132.
- 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.
- Use Diff in Diff to obtain reliable estimates. Mostly across time, but also using within country variation.

SUBSTANTIAL NATURAL VARIATION



METHODOLOGY

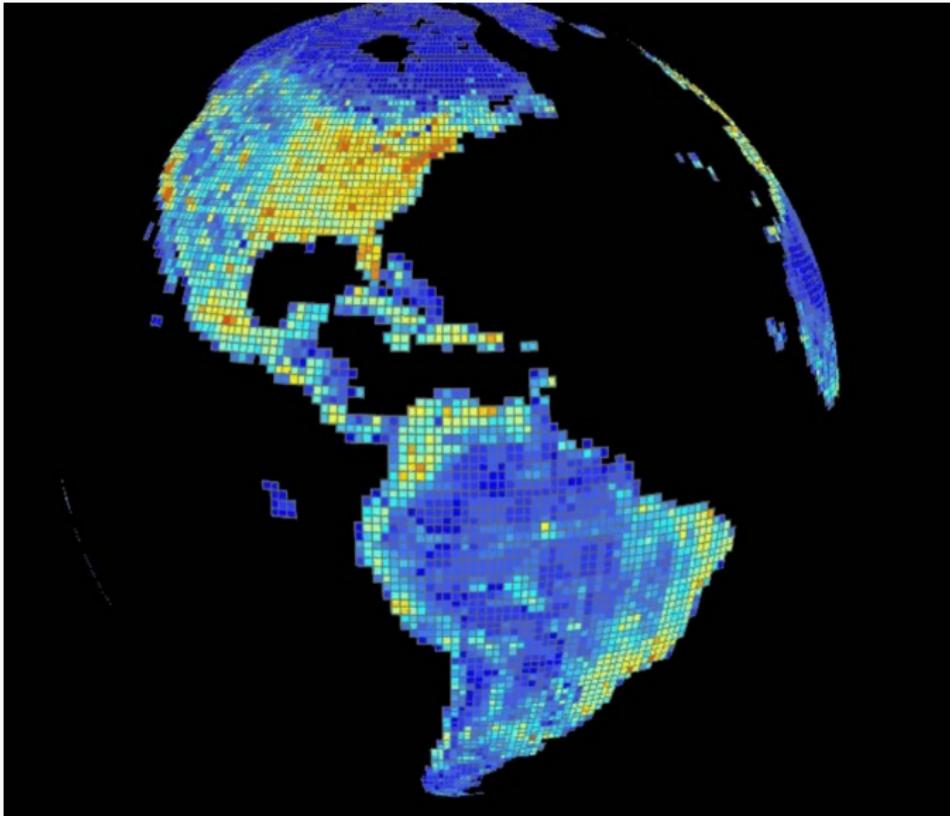
- Assume

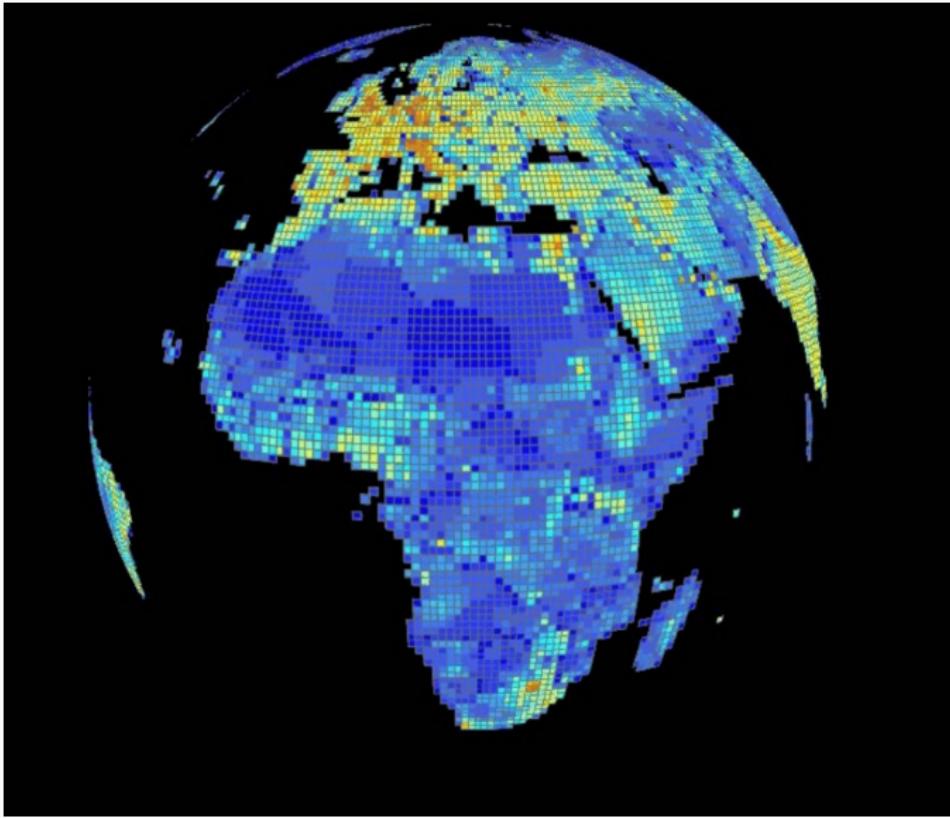
$$Y_{it} = e^{\beta T_{it}} A_{it} L_{it}; \beta \text{ captures level damage}$$
$$\frac{\Delta A_{it}}{A_{it}} = g_i + \gamma T_{it}; \gamma \text{ captures growth-rate damage}$$

- Strong effects: 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 sufficiently poor countries.
- Krusell and Smith (prel.) find other results: only level effects and no difference between poor and rich.
- Crucial feature is whether there are growth effects or not.

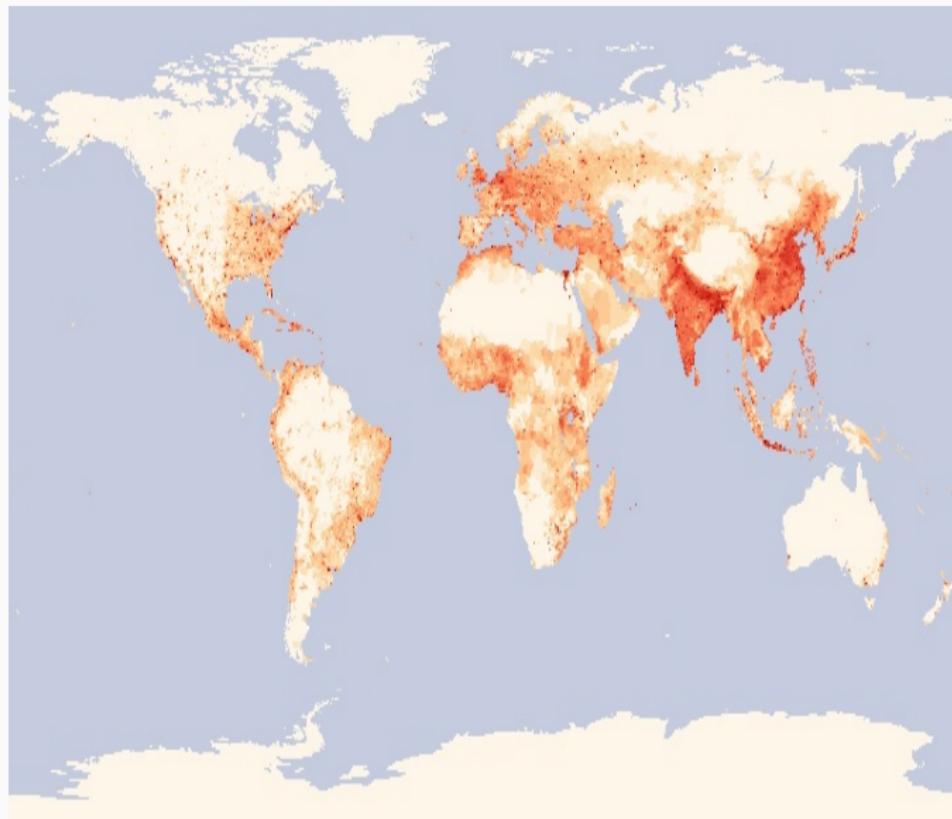
TEMPERATURE-GDP CORRELATIONS WITH HIGH-RESOLUTION DATA

- 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!





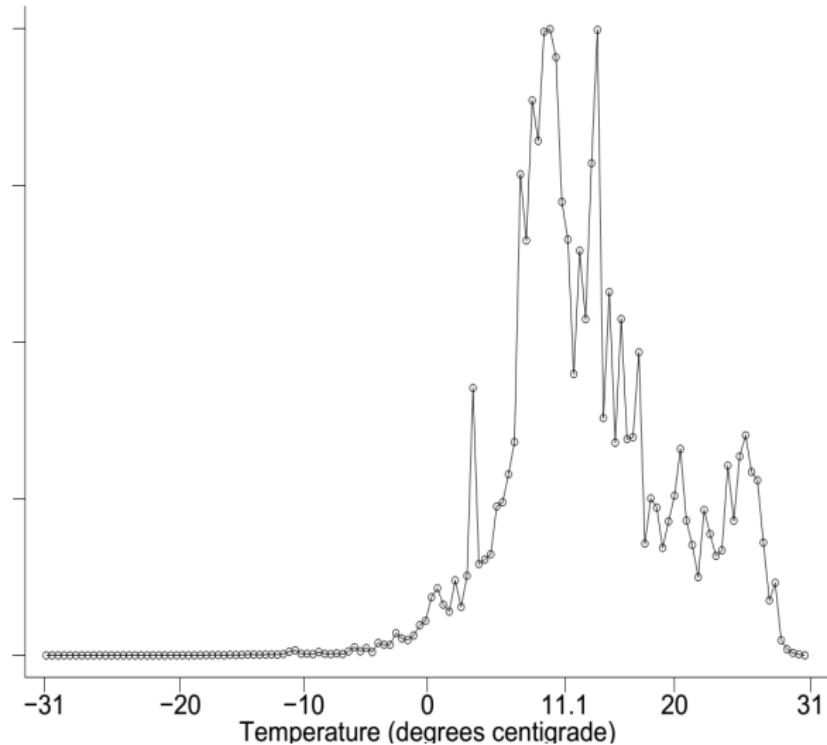
POPULATION DENSITY



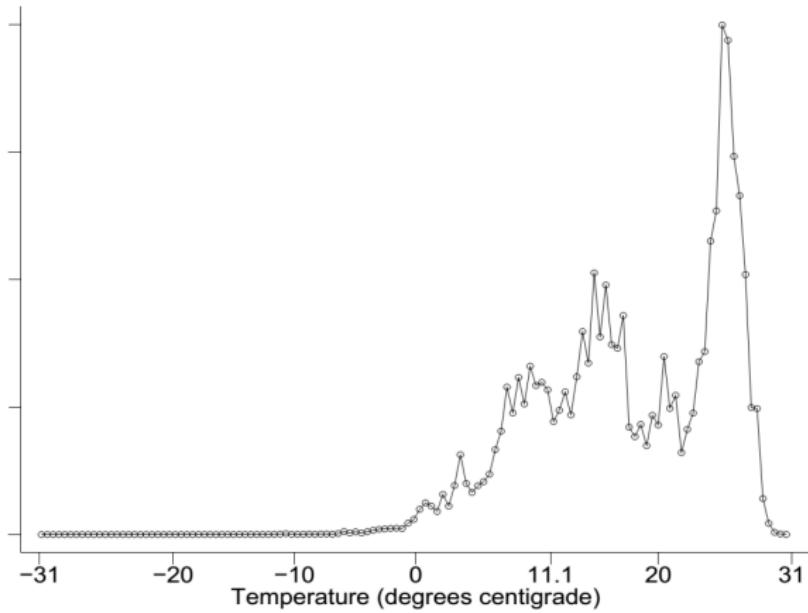
CLIMATE DATA AND PROJECTIONS

- 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



Population as function of local temperature



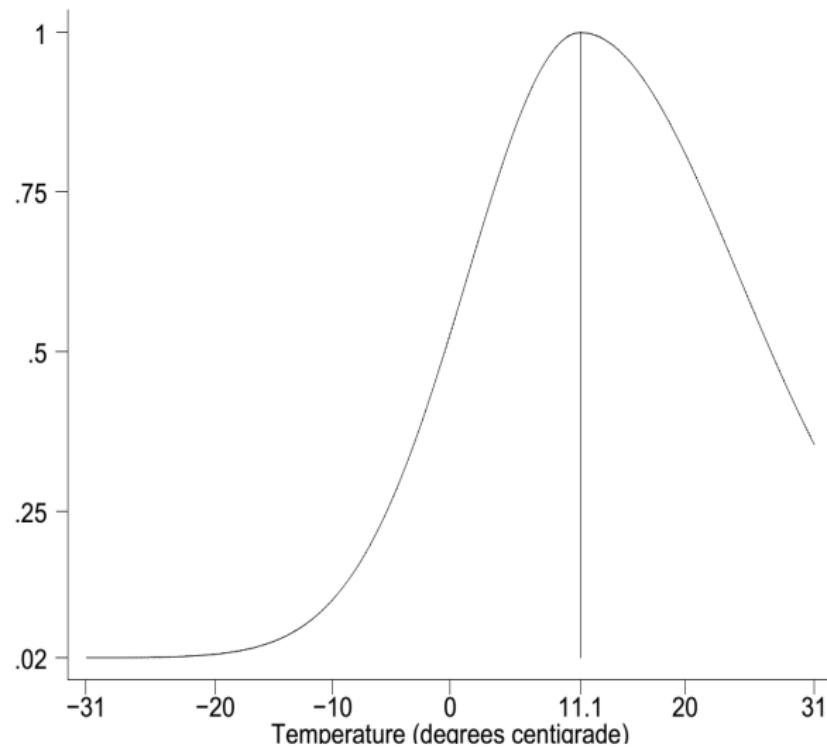
DAMAGE FUNCTION: CALIBRATION

- ① Assume potentially U-shaped damage function (damages output proportionally) in regional temperature T_j

$$D(T_j) = \begin{cases} 1 - \left(p + (1-p)e^{\gamma_h(T_j - T^*)^2} \right) & \text{if } T_j < T^* \\ 1 - \left(p + (1-p)e^{\gamma_l(T_j - T^*)^2} \right) & \text{if } T_j > T^* \end{cases}$$

- ② Apply same function to all regions (so there's an "ideal temperature").
- ③ Use climate predictions from ensemble of climate models to derive reduced-form relation global-regional temperature change (statistical downscaling): $T_j = f_j(T)$.
- ④ For each region, calculate damages at different global mean temperatures.
- ⑤ Aggregate damages and choose $(T^*, \gamma_h, \gamma_l, p)$ to match aggregate damages implied by Nordhaus's DICE damage function.

IMPLIED 1 - (DAMAGE FUNCTION)



REGIONAL EFFECTS OF CLIMATE CHANGE

- Climate change affects regions very differently. Stakes big at regional level.
- In a recent paper, Krusell and Smith (2016) argue that although a tax on carbon would affect welfare positively in some average sense, there is a huge disparity of views on such a tax: 55% of the world's regions will be hurt and 45% benefit from climate change.
- Consequently, there are also strong indications that there will be significant migration pressures from climate change.

CONCLUSIONS OF THE IMPACT OF CLIMATE CHANGE ON THE ECONOMY

- Empirical support for substantial effects on the economy from climate change.
- Effects can be large in particular regions.
- Evidence does not point towards very large effects for moderate heating (< 4 degrees).
- Very little is known for more extreme scenarios.
- At least for moderate heating, percentage marginal damages per unit of extra ton in atmosphere may be approximately constant.
- Much to be learnt from further research.

What to do?

How to design a (common) optimal policy?

MAIN GOAL

- Consider a world with a global externality: using fossil fuel for energy creates carbon dioxide.
- Energy is a required input for the production technology.
- Goal: Derive the optimal policy —here a tax on carbon— so that the externality is internalized.

EXTERNALITY

- Higher levels of carbon dioxide in the atmosphere contributes to global warming, which in turn causes damages like production shortfalls, poor health or deaths, capital destruction and much more.
- Map carbon concentration to climate, and then map climate to damages.
- **Expected sum of future damage elasticities:** the percentage change in output resulting from a percentage change in the amount of carbon in the atmosphere, caused by emitting a unit of carbon today.
- Discounted because of time preferences and because of carbon depreciating.

THE CARBON CYCLE

Carbon circulation system: carbon is exchanged through various reservoirs such as the atmosphere, the terrestrial biosphere, and different layers of the ocean.

The representation of the carbon cycle in this paper is given by the equation:

$$(1 - d_s) = \phi_L + (1 - \phi_L)\phi_0(1 - \phi)^s$$

- ϕ_L : the share of carbon that stays in the atmosphere forever
- $(1 - \phi_0)$: of the carbon that does not stay in the atmosphere forever, this is the share that exits the atmosphere into the biosphere or ocean within a decade
- the remaining carbon in the atmosphere, $(1 - \phi_L)\phi_0$, decays at a geometric rate ϕ

CONSTRUCT A GENERAL EQUILIBRIUM MODEL WITH VARIOUS INGREDIENTS

- ① A joint model of the climate and the economy.
- ② Production Process (GDP) affected by Climate Change
- ③ Households with preferences (needed to evaluate outcomes)
- ④ Explicit use of energy that both contributes to GDP and emits CO₂
- ⑤ Inclusion of Exhaustible Resources that induces savvy economic behavior.

PRODUCTION PROCESS

- Technology $Y_t = F_t(K_t, N_t, E_t, S_t)$
- There are many types of energy inputs $E_{j,t}$, $j = 1, \dots, J$
- The first $J_g - 1$ sectors are “dirty” and the last one is “clean” energy
- For the dirty energy firms, $E_{j,t}$ is normalized so that one unit of $E_{j,t}$ produces one unit of carbon. Emissions are $\sum_{j=1}^{J_g-1} E_j$
- $E_t = \sum_{j=1}^J E_{j,t} \alpha^j$, Actual amount of energy used
- Some energy resources have a finite stock, which is accounted for by the constraint $R_{j,t+1} = R_{j,t} - E_{j,t}^j \geq 0$
- Dirty energy has cost constant cost ξ_j . Clean energy has convex cost $\xi_J(E_{J,T})$.

EVOLUTION OF THE CLIMATE

- The climate variable S_t is the amount of carbon in the atmosphere.
- Depends on past emissions as in the reduced form way
- Define a function \tilde{S}_t that maps the history of man made pollution into the current level of carbon dioxide.

$$S_t = \tilde{S}_t \left(\sum_{j=1}^{J_g-1} E_{j,-T}, \sum_{j=1}^{J_g-1} E_{j,-T+1}, \dots, \sum_{j=1}^{J_g-1} E_{j,t} \right)$$

- Here, $-T$ is defined as the start of industrialization.

MAIN ASSUMPTIONS

- ① $U(C) = \log(C)$
- ② $F_t(K_t, N_t, E_t, S_t) = [1 - D_t(S_t)] \tilde{F}_t(K_t, N_t, E_t)$
(has already subtracted the costs ξ_j of producing energy source j)
- ③ Damages: $[1 - D_t(S_t)] = \exp\{-\gamma_t(S_t - \bar{S})\}$
- ④ The function \tilde{S}_t is linear and has the depreciation structure:

$$S_t - \bar{S} = \sum_{s=0}^{t+T} (1 - d_s) \sum_{j=1}^{J_g-1} E_{j,t-s}$$

- ⑤ $(1 - d_s) = \phi_L + (1 - \phi_L)\phi_0(1 - \phi)^s$

WHAT IS THE BEST THAT CAN BE DONE?

- It is found by solving a social planner's problem
 - Representative household of the world
 - Technological, Climate and Exhaustability Constraints
- After that we worry about implementation

PLANNER'S PROBLEM

$$\max_{\substack{\{C_t, N_t, K_{t+1}, R_{j,t+1}, \\ E_{j,t}, S_t\}_{t=0}^{\infty} \geq 0}} \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t U(C_t) \quad \text{s.t.}$$

$$C_t + K_{t+1} = F_t(K_t, N_t, E_t, S_t) + (1 - \delta)K_t \quad \text{FB}$$

$$E_t = \sum_j E_{j,t} \alpha^j \quad \text{AGE}$$

$$R_{j,t+1} = R_{j,t} - E_{j,t} \geq 0 \quad \text{for all } j \quad \text{ExE}$$

$$S_t = \tilde{S}_t \left(\sum_{j=1}^{J_g-1} E_{j,-T}, \sum_{j=1}^{J_g-1} E_{j,-T+1}, \dots, \sum_{j=1}^{J_g-1} E_{j,t} \right) \quad \text{CC}$$

NOTATION FOR THE PLANNER'S PROBLEM

- $E_{j,t}$ is output of Energy of Sector (type) j measured in units of carbon emitted.
- α^j Conversion of units of energy of type j from being in terms of carbon emissions to units of energy.

CHARACTERIZATION OF THE SOLUTION

- The marginal externality damage is the same for all j :

$$\Lambda_t^s = \mathbb{E} \sum_{i=0}^{\infty} \beta^i \frac{U'(C_{t+i})}{U'(C_t)} \frac{\partial F_{t+i}}{\partial S_{t+i}} \frac{\partial S_{t+i}}{\partial E_{j,t}}$$

- Under our specific assumptions, this expression simplifies to:

$$\Lambda_t^s = \mathbb{E} \sum_{i=0}^{\infty} \beta^i C_t \frac{Y_{t+i}}{C_{t+i}} \gamma_{t+i} (1 - d_i)$$

- Further, if the planner's problem implies a constant savings rate, then the expression can be written as:

$$\Lambda_t^s = Y_t \left[\mathbb{E} \sum_{i=0}^{\infty} \beta^i \gamma_{t+i} (1 - d_i) \right]$$

CHARACTERIZATION OF THE SOLUTION II

- The FOC of the planner says

$$\alpha_j \frac{\partial F_t}{\partial E_t} - \xi_j - \Lambda_t^s = 0$$

DECENTRALIZED EQUILIBRIUM: CONSUMERS

$$\max_{\{C_t, N_t, K_{t+1}\}_{t=0}^{\infty}} \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t U(C_t)$$

subject to

$$\mathbb{E}_0 \sum_{t=0}^{\infty} q_t (C_t + K_{t+1})$$

$$= \mathbb{E}_0 \sum_{t=0}^{\infty} q_t ((1 + r_t - \delta) K_t + w_t N_t + T_t) + \Pi_t.$$

DECENTRALIZED EQUILIBRIUM: FIRMS

$$\Pi_0 = \max_{\{K_t, N_t, E_t\}_{t=0}^{\infty}} \mathbb{E}_0 \sum_{t=0}^{\infty} q_t \left[F_t(K_t, N_t, E_t, S_t) - r_t K_t - w_t N_t - \sum_{j=1}^J p_{j,t} E_{j,t} \right]$$

OPTIMAL TAX

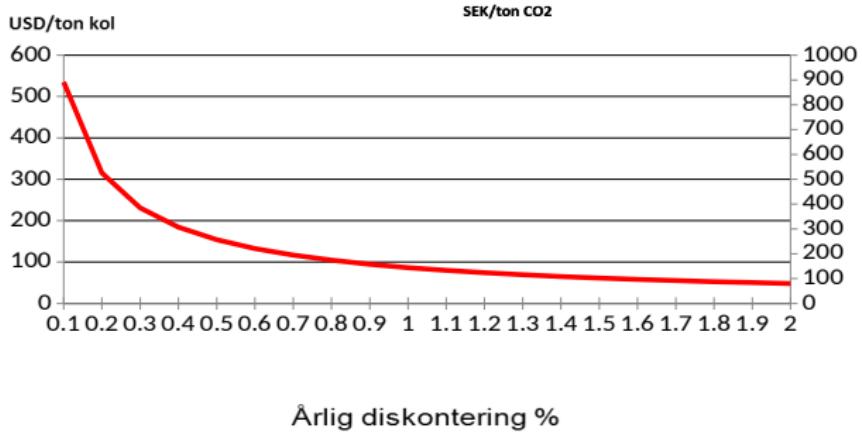
- $\tau_{j,t} = \Lambda_t^s$ for the “dirty” energy firms, and $\tau_{j,t} = 0$ for the “clean” energy firms.
- **This is the optimal first best tax on carbon emissions.**
- If there are multiple externalities (for instance an R&D component to the model) then a separate Pigouvian tax is required for each externality.

COMPARING THE OPTIMAL TAX RATES

To understand the magnitude of the optimal tax rates given by this model, they can be compared with estimates from other models, and also with tax rates that are currently being used around the world.

- Nordhaus (2008) uses a discount rate of 1.5% and gets a tax of \$30 per ton of coal. With the same discount rate, this paper gives a tax of \$56.9 per ton of coal.
- Stern (2007) uses a discount rate of 0.1% and gets a tax of \$250 per ton of coal. With the same discount rate, this paper gives a tax of \$500 per ton of coal.
- In Sweden, the current tax on private consumption of carbon exceeds \$600 per ton of carbon, which is larger than the estimates for the optimal tax in this paper. However, these taxes are significantly higher than many other countries, for instance the EU has a tax of around \$77 per ton of carbon.

Sum damages over time => "optimal" tax!



Sweden has carbon tax ~ 600 USD/tC!

WHAT IF WE DON'T USE THE OPTIMAL TAX?

- Let's use a recent (natural science-based) approximation of the effects on global temperature of fossil-fuel emissions.
- "Carbon Climate Response (CCR): for each 1,000GtC in cumulative historic emissions, global temperature rises by 1-2.1 degrees Celsius (1.8-3.8F).
- We have emitted about 550GtC so far (since industrial revolution).
- Remaining (conventional) oil+gas: about 300GtC. Limited warming if we use it up!
- Remaining coal: much more, possibly over 3,000GtC.
- => Coal is the main threat!

WHAT WOULD THE OPTIMAL TAX DO?

- Wouldn't affect (conventional) oil and gas use.
 - A tax on oil and gas makes little difference: these fuels are so cheap to produce that markets will keep using them despite the tax.
 - It is indeed efficient from an economic perspective to use them up!
- A different story for coal:
 - Coal doesn't give a big profit per unit so a tax would make us stop using most of the coal.
 - Taking the climate damage into account, using coal simply isn't worth it.
- So: bad for the coal industry (the world over), no big deal otherwise

How COSTLY IS THE OPTIMAL TAX FOR US?

- Suppose we use “very cautious” discounting of 0.1%, implying a tax of \$600/tC.
- Turns out Sweden has had that tax for over a decade. They did better than average during the Great Recession, no noticeable “leakage” of firms abroad.
- Significant scope for
 - Energy saving
 - Alternative technology

POLICY INSTRUMENTS

- Baseline recommendation:
 - Tax carbon, world-wide
 - Required rate will not be a big blow to our global economy, but will (must) shake up coal industries
- What about alternatives, like cap-and-trade?
 - If managed so that the emission rights are as expensive as the carbon tax, ok!
 - In Europe, this is not the case —low world demand and high caps culprits.
- Do we need green subsidies?
 - Under an optimal carbon tax, maybe not; otherwise, yes.
- Should all countries mainly reduce emissions at home?
 - No: reduce them where they are least needed/least efficient (e.g., buy emission rights in EU trading system, pay to keep forests, ...)

CLIMATE CHANGE AND ECONOMICS: A SUMMARY

BROAD CONCLUSIONS SO FAR

- climate change likely leads to non-negligible global damages
- very uneven effects across regions of world
- for world as a whole, costs likely not catastrophically large
- a robust result (in Golosov, et al., 2013): optimal policy involves rather modest tax on CO₂ and would not pose threat to economic well-being
- some elements of analysis subject to substantial uncertainty

BASIC NATURAL-SCIENCE LOGIC

- The burning of fossil fuel (oil, coal, natural gas) increases the CO_2 concentration in the atmosphere.
- CO_2 in the atmosphere is a greenhouse gas: it lets solar radiation pass through but blocks heat radiation.
- This leads to global warming. The logic is undisputed among scientists.
- The direct warming effect is significant, but not catastrophic.
- There are, however, feedback effects: creation of water vapor, melting of ice caps lowering solar reflection, cloud formation,
- The quantitative magnitudes of feedback are disputed. The “average” view seems to be that feedbacks strengthen the direct warming effect considerably, but there is much uncertainty.

- Global warming affects economic activity; in many places, the effect is to cause damages (to agriculture, human health, and so on).
- This is an externality: those emitting carbon into the atmosphere are not charged for the costs.
- Thus, in classical economic terms, we have a failure of markets. The prescription is government intervention: we need to artificially raise the cost of emissions to its proper societal value.
- Main recipe: use a tax. Well-known since Pigou (1920).
- The tax must be global: the externality is global.
- What is the appropriate level of the tax? For this, we use standard cost-benefit analysis.