Economic policy (including monetary policy) and climate change: A review

The Economics of Climate Change

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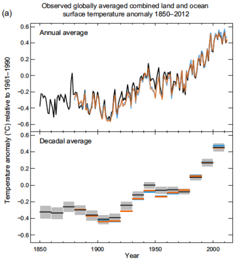
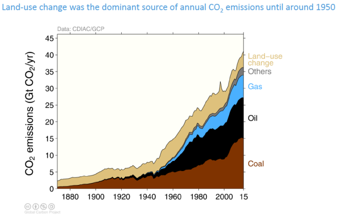
- Climate Change Impacts and Economic Analysis
- Purpose
- Contribution
- Structure

Extensive and well documented scientific evidence suggests that global warming is the result of human activities associated with the use of fossil fuels and the emissions of carbon dioxide (CO_2) and other gasses.



Source: IPCC 2013



Source: The Global Carbon Project, 2016.

- A BAU scenario over the next two centuries is likely to bring changes in climate at a rate that is fast-forward in historical time.
- The science clearly shows that the probability and frequency of floods, storms, droughts, and so on, is likely to continue to grow with cumulative emissions.
- The task of economists is to use climate science and the projected impacts and consider design of policies that will prevent or minimize undesirable events.

The Mother of all Externalities

- In terms of economic analysis climate change is an externality.
- When externalities are present the competitive equilibrium is not Pareto optimal and market failures emerge.
- It is widely accepted that climate change represents the greatest and widest-ranging market failure ever seen.

Some basic characteristics of the climate change externality are:

1. It is global in its origins and impacts. Emissions generated in a certain location have global and not local impacts;

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1. It is global in its origins and impacts. Emissions generated in a certain location have global and not local impacts;
2. Reducing emissions is an extreme “global public good,” meaning that nations will "share" benefits from reduced emissions while the nation that reduces emissions will bear the cost of reduction. This generates free-riding incentives.

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2. Reducing emissions is an extreme “global public good,” meaning that nations will "share" benefits from reduced emissions while the nation that reduces emissions will bear the cost of reduction. This generates free-riding incentives.
3. Some of the effects are very long term and governed by nonlinear dynamics with positive feedbacks.

Economic Policy

- Externality related market failures can be corrected by standard policy instruments: Pigouvian taxes, or allocation of property rights through trading (the Coasian approach).
- Climate change policies follow these basic lines but they should also account a large number of economic considerations
    - estimating damages from climate change;
    - dealing with uncertainty;
    - characterizing impacts on growth and development, and technical change;
    - the need to formulate global policies in the absence of supranational authority and under free-riding incentives,
    - intra and intergenerational distribution which raise important ethical issues.
- Economic policy should also take into account the dynamic interactions between the climate and the economy.

Our Purpose

The present research aims at addressing an important issue that has not been analyzed sufficiently in the economics of climate change. *What is the role of monetary policy under conditions of global warming?*

Because:

- Climate change can affect growth both in terms of output levels and steady-state equilibrium output, but also in terms of output growth through impacts on total factor productivity.
- Economic policy implemented through instruments such as carbon taxes may also affect relative prices

This imposes new challenges to the Central Banks in addition to inflation and output stabilization, because monetary policy needs to take into account that:

1. output and the output gap is affected by global warming
2. relative prices and possibly the general price level might be affected by other climate change policies.

- The main contribution of this research is to bring into the economics of climate change the Central Bank and the monetary policy as an additional tool for designing climate change policy.
- As far as we know systematic research has not been undertaken towards this objective.
- Our intuition, supported by preliminary findings, is that monetary policy could have an important role in helping design efficient climate change policies.

Structure of the Presentation and the Deliverable

- Chapter 2 presents the modeling of climate in the post-industrial period, that is after the anthropogenic influence.
- Chapter 3 presents the way that the economy and climate are modelled as coupled systems
    - Dynamic stochastic general equilibrium models (DSGE) of the economy, without climate change considerations.
    - Integrated assessment models (IAMS)
    - New literature of the environmental macroeconomics without incorporating the Central Bank.
    - We provide a plan for the next steps of our research which aims at developing DSGE models with climate change externalities which would allow us to explore the impact of global warming on monetary policy.

Chapters 4 and 5 present and analyze the two main mitigation related policies for climate change, carbon taxes and cap-and trade policies respectively.
Chapter 6 presents and analyzes adaptation policies.
Chapter 7 addresses some of the most important structural elements of joint models of economy such as, discounting, damages, risk and uncertainty.
Chapter 8 discusses international environmental policy and international agreements.
Chapter 9 concludes and discusses the next steps of our research.

- Energy Balances
- The Link with the Economy

- The modeling of climate and the evolution of temperature is based on energy balance relationships between incoming and outgoing radiation.
- Industrial revolution introduced an anthropogenic perturbation to the energy budget through the use of fossil fuels.
- The perturbation is usually denoted by F (measured in W/m^2) and is called **forcing**. Because of the perturbation, the incoming energy flux is larger than the outgoing flux, which leads to increasing temperature.
- The effects of GHGs can be approximated by

$$F = \frac{\eta}{\ln 2} \ln \left(\frac{S_t}{S_0} \right) \tag{1}$$

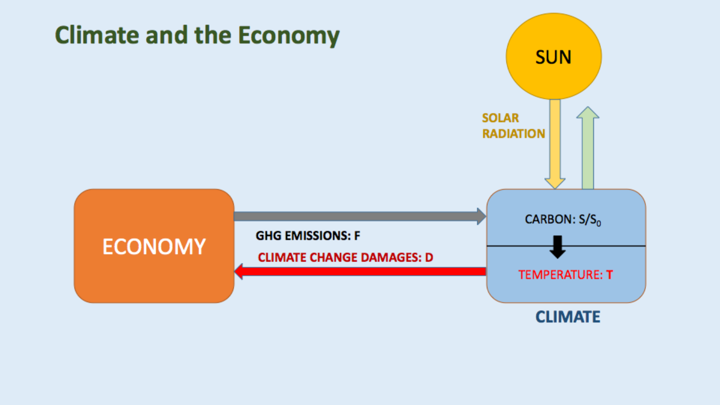
  - $S_t \approx 400$ ppm, $S_0 \approx 288$ ppm.
  - $S_t \approx 840$GtC, $S_0 \approx 600$GtC, 1 Gigatonne $=$ 1 billion tonnes, 1 kg carbon (C) $= 3.644$ kg carbon dioxide (CO_2).

- With constant forcing the equilibrium temperature anomaly is

$$T_\infty = \frac{\lambda}{\ln 2} \ln\left(\frac{S}{S_0}\right) \tag{2}$$

  $\lambda = \frac{\eta}{(\kappa - \xi)}$ is called **equilibrium climate sensitivity** and captures the response in the global mean temperature to a doubling of the CO_2.

- IPCC sets a likely range for λ to $3°C \pm 1.5°C$.


Climate and the Economy
SUN
SOLAR RADIATION
ECONOMY
GHG EMISSIONS: F
CLIMATE CHANGE DAMAGES: D
CARBON: S/S0
TEMPERATURE: T
CLIMATE

Coupled Dynamics

$$\dot{T}(t) = \frac{\lambda}{\ln 2} \ln\left(\frac{S}{S_0}\right) + F_{EX} - \delta T(t) \tag{3}$$

$$F_{EX} : \text{exogenous forcing}, \ T(0) = 0 \tag{4}$$

$$\dot{S}(t) = E(t) - dS(t), \ S(t) = S_0 \tag{5}$$

The coupled dynamics can be expanded by introducing the ocean temperature and taking into account that atmospheric temperature increases much faster than the oceans.

$$\begin{aligned} \dot{T}(t) &= \frac{\lambda}{\ln 2} \ln\left(\frac{S}{S_0}\right) + F_{EX} - \delta T(t) - \sigma_2 \left(T(t) - T^O(t)\right) \\ \dot{T}^O(t) &= \sigma_3 \left(T(t) - T^O(t)\right) \\ \dot{S}(t) &= E(t) - dS(t), \ S(t) = S_0 \end{aligned}$$

Linear Coupled Dynamics

1. The increase in mean global yearly temperature is approximately proportional to cumulated carbon emissions in each of the simulated big climate models.
2. The annual rate of temperature increase is linearly related to the rate of increase of cumulative emissions; this relationship appears to be surprisingly constant over the range of emissions.

$$\Lambda = \frac{\Delta T(t)}{CE(t)}, \tag{6}$$

Λ is called the transient carbon response emissions parameter (TCRE). $\Lambda \approx 1.3$–2.1°C per trillion tones of carbon (TtC) emitted.

$$\dot{T}(t) = \Lambda E(t), \;\; T(0) = 0 \tag{7}$$

- DSGE Models of the Economy
- Integrated Assessment Models (IAM)
- Modern Environmental Macroeconomics
- The DICE2013R model (Nordhaus, 2014)
- The Macroeconomics of Climate Change
- Monetary Policy and Climate Change

- Modern macroeconomic theory starts with the view that growth, cycles and policy need to be studied jointly.
- The main determinant of economic outcomes is agents' dynamic decision problems.
- As Lucas (1976) established, to understand growth, cycles and policy, one needs to use dynamic model economies consistent with rational behavior on the part of economic players and general equilibrium.
- These models (known as RBC models), in contrast to old-style, Keynesian macroeconometric models, are based on microfounded, optimizing behavior and a general equilibrium framework.

- A single consumer-producer chooses a utility maximizing consumption profile:

$$\begin{aligned} E_t \sum_{t=0}^{\infty} \beta^t u\left(c_t\right) &\equiv E_t \sum_{t=0}^{\infty} \beta^t \log\left(c_t\right) && (8) \\ \text{s.t. } c_t + k_{t+1} - \left(1-\delta\right) k_t &= A_t k_t^{\alpha} && (9) \end{aligned}$$

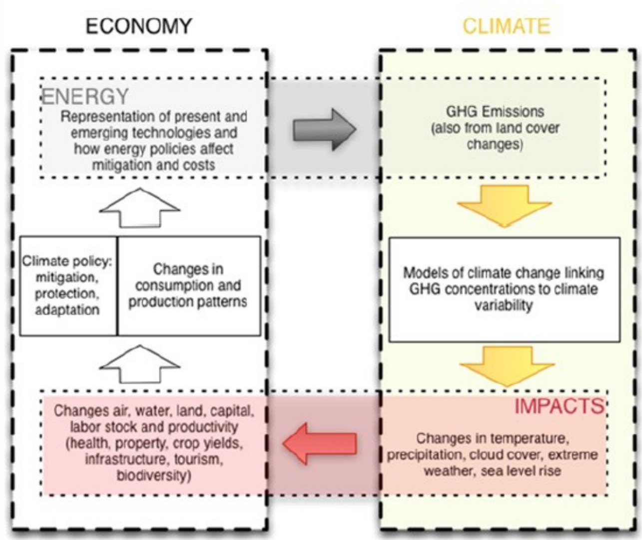
Optimality implies:

$$\begin{aligned} E_t c_{t+1} &= \beta E_t c_t \left(1 - \delta + \alpha A_t k_t^{\alpha-1}\right) && (10) \\ c_t + k_{t+1} - \left(1-\delta\right) k_t &= A_t k_t^{\alpha} && (11) \\ \text{where } A_t &= A_0 e^{z_t} \ , \ z_t = \rho z_{t-1} + \varepsilon_t && (12) \end{aligned}$$

- Hence, the stochastic productivity is the only source of uncertainty in the economy and is the engine of the Real Business Cycle doctrine.

- Recent macroeconomic models also include market imperfections, policy failures, several shocks, etc.
- These models, known as dynamic stochastic general equilibrium (DSGE) (for reviews, see e.g. Cooley and Prescott 1995, King and Rebelo 1999, Rebelo 2005, McGrattan 2006, Kydland 2006).
- Most DSGE models are built around three interrelated blocks (see e.g. Sbordone et al., 2010): a demand block, a supply block and a block related to policy equations.

- The figure below provides a depiction of climate-economy dynamics.
- The climate module describes the link between GHG emission, atmospheric concentrations and the resulting variation in temperature and other climatic changes
- The impacts module (or damage function) expresses physical or environmental outcomes as a function of climate variables.
- An economy module may describe the dynamics or growth of an economy, how emissions vary with growth and climate policies, and how climate-induced physical and environmental changes might affect parts or all of an economy.
- The economy model is often augmented with a more detailed energy module that describes the factors determining the uses of different sources of energy and the cost of emission reductions.



Representation of present and emerging technologies and how energy policies affect mitigation and costs

GHG Emissions (also from land cover changes)

Climate policy: mitigation, protection, adaptation

Changes in consumption and production patterns

Models of climate change linking GHG concentrations to climate variability

Changes air, water, land, capital, labor stock and productivity (health, property, crop yields, infrastructure, tourism, biodiversity)

Changes in temperature, precipitation, cloud cover, extreme weather, sea level rise

The most important IAMs (Gillingham et al. (2015))

- the DICE/RICE model
- the FUND model
- the GCAM model
- the MERGE model,
- the MIT IGSM model, and
- the WITCH model.

- Hassler et al. (2016) discuss climate change and resource scarcity from the perspective of macroeconomic modeling and quantitative evaluation.
- Their focus is to develop a microeconomics-based IAM.
- In contrast the IAMs developed by Nordhaus, (DICE/RICE) are closer to what most people think to be pure planning problems
- Modern environmental macroeconomics models seek to answer the question.
    - What happens if authorities pursue a suboptimal policy?

- Hassler et al. consider a growth economy inhabited by a representative agent, whose intertemporal utility is given by:

$$\sum_{t=0}^{\infty} \beta^t u(C_t, S_t) \tag{13}$$

with a resource constraint of the form:

$$C_t + K_{t+1} = (1-\delta)K_t + F(K_t, E_t, S_t) \tag{14}$$

and where S obeys the following law of motion:

$$S_{t+1} = H(S_t, E_t) \tag{15}$$

- Comparing the optimal path of K and S to the market outcome can be important in the sense that this might reveal the type of policies needed to move the *laissez-faire* outcome toward the optimum.

- Then, the modern macroeconomic approach would be to:
    - define a dynamic competitive equilibrium with policy (say a unit tax on E), with firm, consumers, and markets clearly spelled out
    - look for insights about optimal policy both qualitatively and quantitatively (based on, say, calibration)
    - characterize outcomes for the future for different (optimal and suboptimal) policy scenarios.
- Golosov et al. (2014) use a quite similar model to study the interconnection between the climate and the economy incorporating the climate externality through a fossil fuel sector.

- The DICE model optimizes a social welfare function, W, which is the discounted sum of the population-weighted utility of per capita consumption.

$$\sum_{t=1}^{T\,\max} U[c(t), L(t)]R(t) \tag{16}$$

Net output, $Q(t)$, is a function of gross output, $Y(t)$. Net output is gross output reduced by damages and mitigation costs:
The objective (16) is maximized subject to economic and climate constraints.

- Climate change might have an impact on the macro-economy in two basic ways:
    - by affecting factor stocks and productivity and the growth rates of both; for example floods may damage infrastructure or labour productivity may decline due to increased temperature, and
    - by affecting the way in which agents maximize their objectives; for example demand for health care or air-conditioning may increase, as may uncertainty over future states of the world which affects how households plan, or climate change may affect non-market items that households value such as biodiversity.
- Hence, macroeconomic policy is needed to deal with the above impacts of climate change on economic activity.

Policy instruments for mitigation and adaptation

- Mitigation
  - carbon taxes
  - emissions trading systems
  - subsidies, standards, R&D, Technology Transfer, and other regulatory devices
- Adaptation
  - deliberate adjustments in ecological, social, and economic systems to moderate adverse impacts of climate change and harness any beneficial opportunities.
  - “hard” policy measures (for example dyke construction, changing crop varieties, adapting infrastructure) and “soft” measures (for example early warning systems, building codes, insurance).

The main question is:

> *Can monetary policy make a meaningful contribution to the formulation of climate change policies?*

- Although there are various channels through which climate change may affect the conduct of monetary policy, from the point of view of a central banker, the best way to think about climate change may be as a series of (real) autocorrelated negative supply shocks.
- Each of these negative supply shocks will likely lead to a contraction in the economy's productive capacity, generating higher prices and diminishing growth rates.

- The more persistent these shocks are, the higher the chances that they lead to a permanent reduction of potential output, affecting not only our economies' cycles but also their longer-term trends.
- It is natural to think of agriculture, forestry, fisheries, or tourism, as some of the sectors most likely to be affected by changing weather conditions, but the impact can actually be broader and extend to other sectors and, ultimately, to the whole economy.
- Besides, climate change can have significant effects on trade, capital flows, and migration, as well as on investment and savings.

- Thus climate change is expected to affect output both in terms of transient and steady states.
- This implies that the output gap component of monetary policy rules is affected by climate change and could be "**environmentally adjusted**" so that monetary policy decisions incorporate the impact of climate change on economic activity.

- Taylor type rules:

$$i_t = \bar{i} + \alpha(\pi_t - \pi^*) + \gamma x_t + \varepsilon_t$$

  i_t is the central bank's policy interest rate, $\bar{i}$ is the long-run policy rate, π_t is inflation, π^* is the central bank's inflation target, x_t is output gap, and ε_t is a random variable.

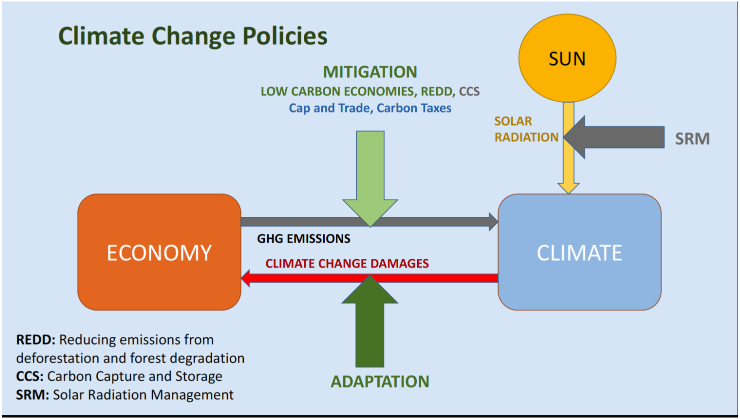
- Schmitt-Grohe and Uribe (2007):

$$\ln(R_t / R^*) = \alpha_R \ln(R_{t-1} / R^*) + \alpha_\pi E_t \ln(\pi_{t-i} / \pi^*) + \alpha_y E_t \ln(y_{t-i} / y^*) \ , \ i = -1, 0, 1$$

  where y^* denotes the nonstochastic Ramsey-steady-state level of aggregate demand

- In this context our research objective is to develop a DSGE - IAM seeking to derive meaningful environmentally adjusted monetary policy rules.
- In this model the government will be responsible for the design and implementation of fiscal and climate policies, while the Central Bank will decide on the design and implementation of monetary policy which could potentially be environmentally adjusted.

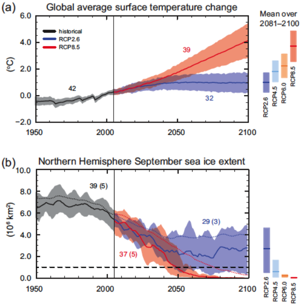
- Representative Concentration Pathways
- Carbon Budgeting
- The Social Cost of Carbon
- Carbon taxes
- CCS
- REDD+



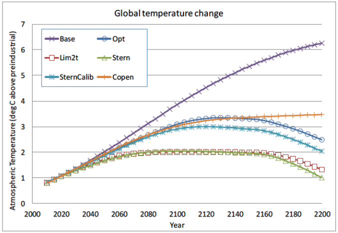
Climate Change Policies

REDD: Reducing emissions from deforestation and forest degradation
CCS: Carbon Capture and Storage
SRM: Solar Radiation Management

Representative Concentration Pathways (RCPs) are scenarios developed by IPCC (see IPCC 2013) that include time series of emissions and concentrations of GHGs, as well as land use/land cover.



Source: IPCC 2013.

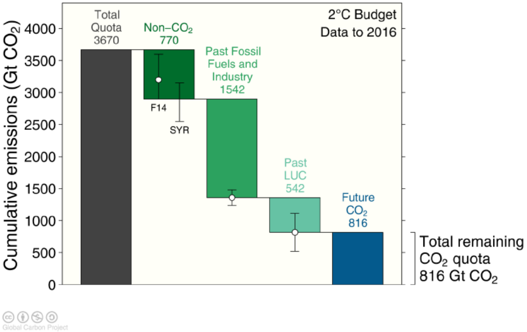


Source: DICE 2013R.

Carbon quota for a 66% chance to keep below

The total remaining emissions from 2017 to keep global average temperature below 2°C ($800GtCO_2$) will be used in around 20 years at current emission rates

Data: IPCC/CDIAC/GCP/Peters et al. 2015



Grey: Total CO_2-only quota for 2°C with 66% chance. Green: Removed from CO_2 only quota. Blue: Remaining CO_2 quota.
The remaining quotas are indicative and vary depending on definition and methodology
Source: Peters et al 2015; Global Carbon Budget 2016

1. How the remaining quota of 816 Gt CO_2 will be allocated among nations. This needs to be resolved by international negotiations and agreements
2. Once the allocation is determined, climate change policies either national or international need to be determined so that markets will produce the desired level of global emissions.

The social cost of carbon (SCC) represents the economic cost caused by an additional ton of carbon dioxide emissions (or more succinctly carbon) or its equivalent.
Thus the SCC is:

$$SCC_t = \sum_{k=2}^{\infty} \frac{1}{(1+\rho)^{t+k}} u'\left(C_{t+k}\right) \frac{\partial C_{t+k}}{\partial T_{t+k}} \left(\sum_{s=1}^{k-1} \frac{\partial T_{t+s}}{\partial S_{t+s}} \frac{\partial S_{t+s}}{\partial E_t} \right) \tag{17}$$

where $u(C)$: utility of consumption C; T global average temperature; S stock of GHGs, E emissions of GHGs, ρ utility discount rate.
Nordhaus (2013) provided a formulation of the SCC which is appropriate for calculating the SCC using the DICE model. In this case the SCC is defined at time t as:

$$SCC(t) = -\frac{\partial W / \partial E(t)}{\partial W / \partial C(t)} \tag{18}$$

An increment of emissions in the second period will generate an alternative path of consumption relative to a base path. The SCC is estimated by the difference in the present value of consumption between the two paths, discounted at an appropriate SDR in period 2, divided by the increment in emissions, That is:

$$SCC_2 = \frac{\sum_{t=2}^{T} \frac{1}{(1+r)^t} \left(C_t^{Base} - C_t^{Incased \ \ Emissions \ \ at \ \ t=2} \right)}{E_2^{Increased} - E_2^{Base}}$$

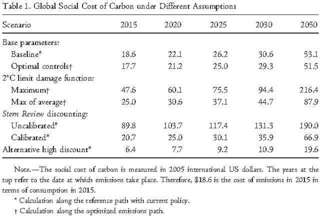


Table 1. Global Social Cost of Carbon under Different Assumptions

Scenario	2015	2020	2025	2030	2050
Base parameters:					
Baseline*	18.6	22.1	26.2	30.6	53.1
Optimal controls†	17.7	21.2	25.0	29.3	51.5
2°C limit damage function:					
Maximum†	47.6	60.1	75.5	94.4	216.4
Max of average†	25.0	30.6	37.1	44.7	87.9
Stern Review discounting:					
Uncalibrated*	89.8	103.7	117.4	131.3	190.0
Calibrated*	20.7	25.0	30.1	35.9	66.9
Alternative high discount*	6.4	7.7	9.2	10.9	19.6

Note.—The social cost of carbon is measured in 2005 international US dollars. The years at the top refer to the date at which emissions take place. Therefore, $18.6 is the cost of emissions in 2015 in terms of consumption in 2015.

* Calculation along the reference path with current policy.

† Calculation along the optimized emissions path.

Source: Nordhaus (2014).

- Optimal carbon taxes correspond to the price of the climate externality in the optimizing models of climate and economy. For example in Golosov et al. (2014) the optimal price of the climate externality is:

$$\Lambda_t^S = \mathbb{E}_t \sum_{j=0}^{\infty} \beta^j \frac{U'\left(C_{t+j}\right)}{U'\left(C_t\right)} \frac{\partial F_{t+j}}{\partial S_{t+j}} \frac{\partial S_{t+j}}{\partial E_t} \tag{19}$$

- Optimal tax calculations are very sensitive to the choice of the discount rate. Nordhaus (2008) using 1.5% as a discount rate suggests \$30 per ton coal, while Stern (2007) using 0.1% suggests \$250 per ton coal. Golosov et al (2014), suggests \$56,9/ton and \$496/ton for the two values of the discount rate.
- In practice carbon taxes are not wide spread and the major instrument is cap-and-trade.

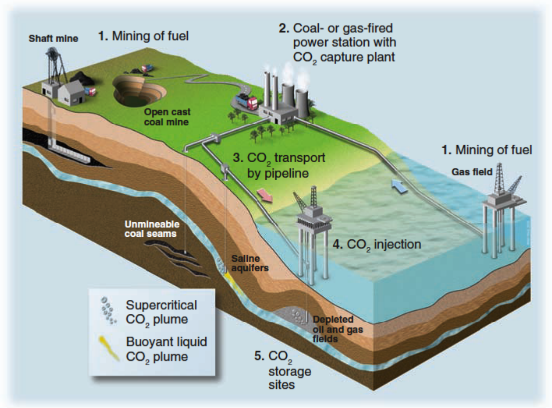
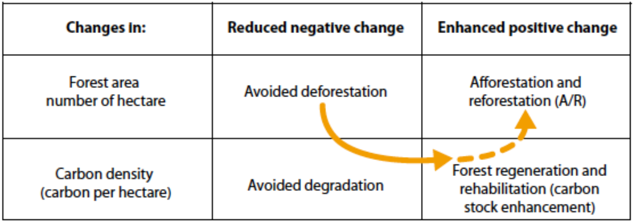


Fig. 1. Diagrammatic representation of the life-cycle chain of fossil fuel use. CO_2 separation and capture at power plants enables storage of CO_2 in porous rocks deep below ground.

Source: Haszeldine, R., (2009).



Changes in:	Reduced negative change	Enhanced positive change
Forest area number of hectare	Avoided deforestation	Afforestation and reforestation (A/R)
Carbon density (carbon per hectare)	Avoided degradation	Forest regeneration and rehabilitation (carbon stock enhancement)

Figure 2.1. Creditable activities in a REDD+ mechanism

Source: Angelsen and Wertz-Kanounnikoff (2008)

Source: Angelsen, A., (Editor) (2009).

The basic theoretical model
Efficiency and Market Power
Existing, Emerging and Potential ETSs
The EU-ETS
Comparison of Taxes to Permits

- Increasing interest in Emissions Trading Schemes (ETSs) is based mainly on the expected efficiency gains derived from allocating abatement effort to the lowest cost facilities.
- Two types of tradable permit policies:
  1. Credit systems: certification of credits to firms that reduce their emission below the existing limits; certified credits can either be sold to other firms or banked to be used in subsequent periods.
- ETSs were introduced initially at the national level –mainly in the USA– and later, following the positive evaluation of the existing schemes, at the international level, the primary example being the EU-ETS for controlling greenhouse gases.

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- Two types of tradable permit policies:
  1. Credit systems: certification of credits to firms that reduce their emission below the existing limits; certified credits can either be sold to other firms or banked to be used in subsequent periods.
  2. Cap and trade systems: the regulator defines the total level of allowable emissions, assigns allowances to them and distributes them (either free of charge, grandfathering, or through an auction) to firms; allowances (permits) can be traded among firms.
- ETSs were introduced initially at the national level –mainly in the USA– and later, following the positive evaluation of the existing schemes, at the international level, the primary example being the EU-ETS for controlling greenhouse gases.

- Assuming perfect competition, the price at which permits are traded P^* will be determined at the intersection of the market demand for permits with the fixed supply of permits. Each firm i emitting initially E_i units of pollutant and with marginal cost of abatement $MAC_i(E_i)$, will engage in abatement up to the point that the last unit of abatement costs the same as purchasing a permit, and thus, any firm i will emit E_i^* units of pollutant (abating E_1-E_i^* units) and will purchase the respective number of permits. At the equilibrium,

$$MAC_i(E_i^*) = P^*, \ \forall i = 1, ..., n,$$

- Trading permits achieve efficiency (cost effectiveness) regardless of whether permits are auctioned off or allocated free-of-charge to the firms and in the latter case, regardless of the particular initial allocation rule that is used.

- The efficiency properties of ETS are distorted when there is market power either in the product or the permit markets.
- Sartzetakis (1997b) and (2004) shows that if product market is oligopolistic, even in the case of perfectly competitive permits markets, efficiency is not achieved.
- Stavins (1995) incorporated transaction costs into the basic permits model to establish that cost efficiency conditions are violated and thus, the full potential of the permit market is not achieved.

- The first applications of ETSs were intended to control local and regional air pollutants, notably SO_2 and NO_X and were introduced some thirty years ago in the United States.
- More recently ETSs were introduced to regulate greenhouse gases, mainly carbon dioxide (CO_2).
- Over the years there is a variety of applications for tradable permits markets in a number of countries, including water use (groundwater permits) and pollution control (salt discharge permits) and fishery permits

- The EU ETS is the largest cap-and-trade program in terms of:
    - the countries participating (the 28 EU Member States, Iceland, Liechtenstein and Norway),
    - emissions covered (carbon dioxide (CO2) emissions, nitrous oxide (N2O) emissions from all nitric, adipic, glyoxylic acid and glyoxal production and perfluorocarbons (PFC) emissions from aluminium production),
    - sources under obligation.
- It caps the volume of greenhouse gas emissions from installations and aircraft operators responsible for around 45% of EU greenhouse gasses

Three Phases

1st phase (2005 - 2007): pilot phase, establishing the necessary infrastructure (monitoring, reporting and verification),

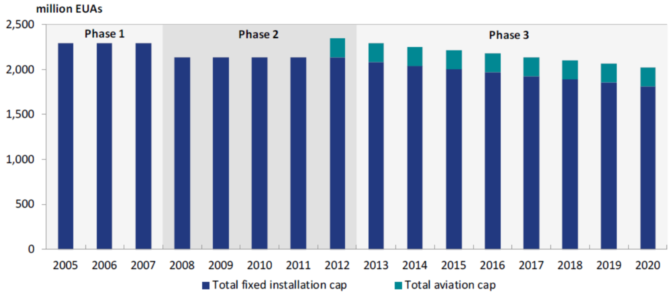
2nd phase (2008 - 2012): and established the effective functioning of the market,

3nd phase (2013 - 2020): improving the scheme based on lessons learned from the previous two phases.

Main changes of the EU-ETS

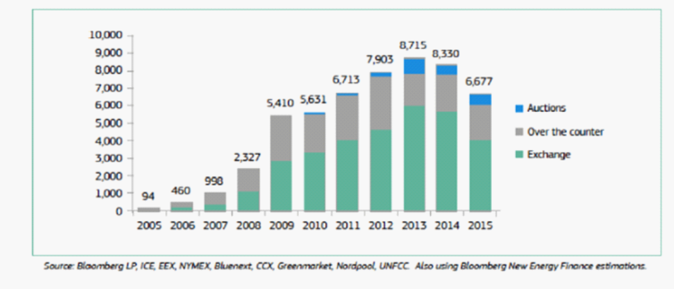
1. moving gradually from grandfathering to auctioning (starting the phasedown with electric utilities),
2. moving from national registries to EU registry
3. adopting a single EU-wide cap decreasing each year by 1.74% relative to the average number of permits issued annually in 2008-2012,
4. and changes in the offsets (CDMs and JIs) that limit their use.

- There are more national or sub-national systems already operating or under development in Canada, China, Japan, New Zealand, South Korea and Switzerland.



Emission caps during the three phases of the EU ETS (Source: European Commission 2015).

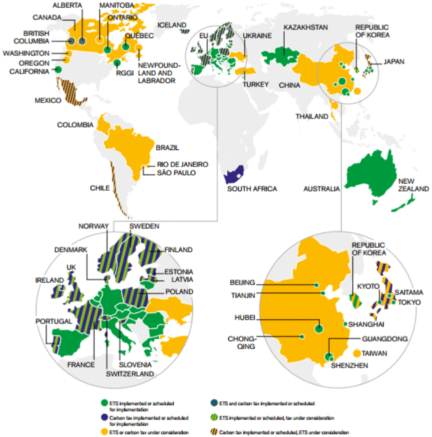
The evolution of the EU carbon price: (Source: sandbag, smarter climate policy).



Source: Bloomberg LP, ICE, EEX, NYMEX, Bluenext, CCX, Greenmarket, Nordpool, UNFCC. Also using Bloomberg New Energy Finance estimations.

Trading volume of EU ETS allowances up to 2015, in $MtCO_2 - eq$..

- Revenues from auctioning for the Greek state were €488 703 520 (€6 090 795 from aviation allowances). (European Commission 2015).
- One important problem that has been identified is the creation of a substantial allowances surplus.
- The Commission is planning to create a market stability reserve which will become operational in 2019. The main goal of the reserve is to adjust the number of auctioned allowances, so as to absorb any major socks (such as the economic recession).



Summary map of existing, emerging and potential regional, national and subnational carbon pricing initiatives (ETS and tax) (Source: World Bank (2016).

- Experience with cap-and-trade systems up to now provides mixed results as to their effectiveness in curbing emissions while less debatable is their cost efficiency.
- In the existing ETSs there is little evidence of market power distortions, but considerable evidence of distortions due to transaction costs.
- The EU ETS has received a lot of praise and acknowledgement for achieving emission reductions in a cost effective way, it also received significant criticism focused mainly on two issues:
- "windfall profits": increased prices of electricity which resulted in higher corporate profits mainly due to the free allocation of allowances and market power,
- "over-allocation.": not sufficiently stringent emissions cap.

Lessons learned:

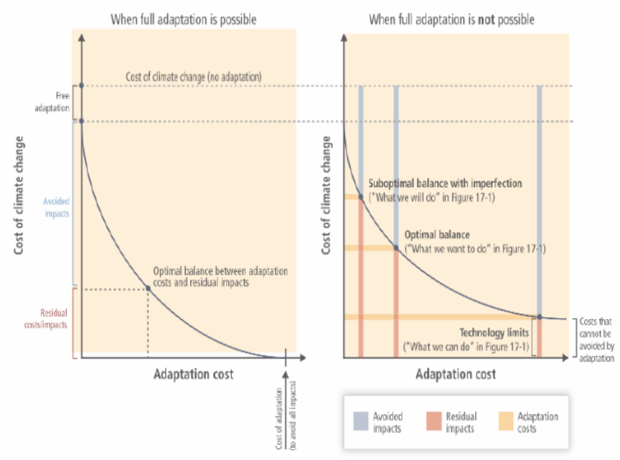
- move to auctioning of permits, since it increases the cost of price manipulation and most importantly generates significant public revenues,
- establish ceilings and floors to the permit price (through the release of reserved allowances when price increases and an auction reservation price) in order to decrease the volatility of permit price,
- increase the market size by linking different regional, national and sub-national markets, since the wider the market coverage is, the less vulnerable the market will be to problems of market power and transaction costs

- Environmental taxes and tradable emission permits are, in the absence of other distortion, theoretically equivalent in terms of achieving the optimal level of emissions at the lowest possible cost (Baumol and Oates 1988 and Xepapadeas 1997).
- However, the equivalence breaks if there is uncertainty over benefits and costs. Weitzman (1974) shows that, under cost uncertainty, the efficiency of a tax relative to an ETS depends on the pattern of costs and benefits. Hybrid systems may perform better.

- Adaptation Economics
- Mitigation-Adaptation
- Private Adaptation
- Public Adaptation
- Analytical and Empirical Methods to Study Adaptation
- Climate Adaptation Policy Instruments
- Adaptation Finance

- The importance of adaptation has grown as an issue because of the inadequate effort to mitigate climate change and the fact that even if the global community achieves the aspirations set in the Paris agreement severe impacts will occur in the following century.
- From the perspective of a small country, e.g. Greece, the carbon output is usually too small to have a tangible impact on climate change. In this case, climate change is taken as a given or exogenous and mitigation policy has largely been set as part of a commitment within a global or other agreement. Thus adaptation action will be designed to address residual climate change but should also take into account potential complementarities with mitigation and non-climate policies.
- Failure of private or market adaptation provides a rationale for public action whether in the form of correcting the market, or supplanting the market through the provision of adaptation that is public good in nature.

- Benefits of adaptation involve the reduction in damages from climate change along with any climate-related gains (Bank 2010b).
- Costs of adaptation refer to all resources spent to develop, implement and maintain adaptation action.
- From a global perspective there are broadly speaking two responses to climate change.
  - **Mitigate climate change or adapt to a changing climate**.
- The optimal action would be to choose that mix of mitigation, adaptation and residual climate damage that minimizes the total welfare loss associated with climate change.
- Given that mitigation is a global public good, determining a global allocation of effort between mitigation, adaptation and residual damages that minimizes world welfare loss necessitates a vantage point of global welfare. It is a collective choice problem of the grandest scale.



Adaptation and residual cost of climate change

Source: Chambwera et al., 2014)

- IAMs confirm that effective action involves both adaptation and mitigation (De Bruin et al. 2009b; Agrawala 2011; Bahn et al. 2012) though there is little agreement on their relative effectiveness.
- Mitigation benefits tend to have longer lead times because of the inertia in both economic and climate systems (Bosello et al. 2010) suggesting that mitigation interventions should precede adaptation.
- When models distinguish between proactive adaptation (also called stock adaptation) and reactive adaptation (flow adaptation) there is more of a balance in sequencing of adaptation and mitigation. These models generally suggest that mitigation should come earlier than adaptation.
- Higher discounts have a stronger effect on mitigation while climate uncertainty may favour later adaptation.

- Private adaptation refers to actions that firms and individuals take in response to climate change.
- Efficient private adaptation implies that individuals maximize their net benefits in response to weather and climate change.
- The response of agents to climate risks may be inadequate or even lead to worse outcomes (maladaptation) because of:
  - Transaction costs, information costs.
  - Positive externalities and the public good nature of many adaptation goods.
  - The lack of well defined or secured property rights.
  - Insurance coverage may give rise to moral hazard with agents ignoring or taking inadequate precautions with respect to climate risks.
  - Cognitive issues.
- Failures of private adaptation are likely to be even more accentuated in low-income countries and populations.

- Imperfect private adaptation and the fact that some benefits of adaptation are in the nature of public goods provides a rationale for government action in:
  - Coastal protection,
  - Water management,
  - Conservation, climate information services (Collier et al. 2008),
  - Sea walls or river levees that limit flooding to private land holders (Ranger et al. 2013),
  - Infrastructure to deliver water supplies,
  - Disease control or medical assistance to limit epidemics,
  - Climate-proofing of conventional public goods like transport networks (Dietz & Dixon 2016).
- Provision of these public goods will generate benefits to many.

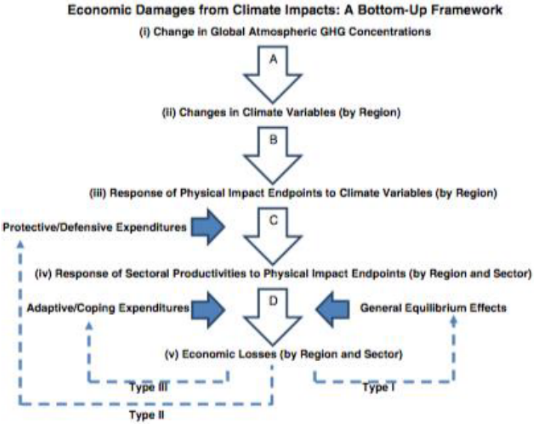
- Another important role for public policy is assistance for vulnerable groups that may not have the means to adequately adapt or more generally the need to account for distributional matters when conducting public adaptation policy.
- However, while governments are usually looked upon to correct market failures whether through providing the institutional and incentive framework to correct them, by direct provision of adaptation public goods, or helping with behavioral and cognitive biases, they are also prone to failures (Krueger 1990).

- Many of the same tools used for understanding the impacts of climate change and evaluating alternative mitigation policies are also used for understanding the challenges for adaptation policies (as these derive from projected impacts), the degree of substitutability between adaptation and mitigation as well as the potential complementarities of mitigation and adaptation policies, or the costing of adaptation policies.
- IAMs have been modified to include adaptation. One approach is the modification of the damage function:

$$D\left(T\right) = \arg\min_{A}\left[AC\left(A, T\right) + RD\left(A, t\right)\right] \tag{20}$$

where A is adaptation effort, T is global mean temperature, AC denotes adaptation costs, and RD residual damages.

- On the other hand "no study has accounted for the implications of impacts and adaptation for the climate stabilization strategies" (Fisher-Vanden et al. 2014). The omission of adaptation responses from analysis can bias the results because:
    - The economic costs of climate impacts can be dampened by adaptation,
    - The baseline emission trajectory could be changed by adaptation, e.g., the use of air conditioning could increase emissions
    - Investments in adaptation could crowd out mitigation and thus make it more expensive.
- Support of adaptation decision making at the sectoral level usually relies on studies that follow an econometric or simulation approach.
- For purposes of financing adaptation, models have attempted to cost adaptation at the global, regional and sectoral level.



Adaptation adjustments to IAMs

Source: (Wing and Fisher-Vanden, 2013)

- While the potential for the use of economic instruments to promote adaptation is widely recognized there is a paucity of literature. Four classes of incentive-providing instruments have been identified (Agrawala & Fankhauser 2008; Chambwera et al. 2014):
    1. Insurance schemes for extreme events;
    2. Price signals/markets for water and ecosystems;
    3. Regulatory measures and incentives like building standards and zone planning;
    4. Research and development incentives for agriculture and health.

- When it comes to climate adaptation finance there is a substantial literature on the question of the international financing of adaptation of the developing economies or the support of climate-resilient development.
- This has given rise both to an interest in effective adaptation strategies and the best ways to finance these. Accordingly, studies have looked at ways of costing adaptation at the global, regional, national, local and sectoral levels with an eye to determining financing needs.
- Other concerns include the economics of raising adaptation finance, the governance of those funds, and the allocation to competing needs (Fankhauser 2017).
- Finally, adaptation finance (in this context of the responsibility towards developing countries) is meant to provide over and above traditional development assistance but this raises numerous analytical complications.

- The Discounting Process
- Modelling Climate Change Damages
- Risk and Uncertainty
- Regional Issues
- Spatial Models of the Economy and the Climate

The Social Discount Rate: The Ramsey Rule

The SDR is used in Cost-Benefit Analysis and is very important in evaluating environmental related projects such as investment in adaptation. The SDR for the Ramsey rule is:

$$r = \rho + \eta g \tag{21}$$

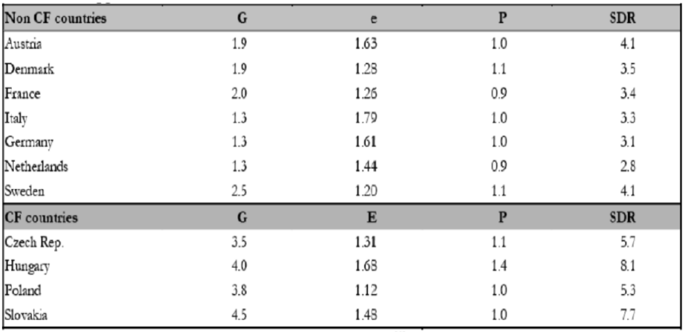
where ρ is the social rate of time preference, η is the elasticity of marginal utility, and g is the rate of growth of per capita consumption.

ρ Values used: Cline (1992): $\rho = 0$; Nordhaus (1994) $\rho = 3.0\%$ per year, DICE(2007), RICE (2011) $\rho = 1.5\%$ per year, Stern $\rho = 0.1\%$ per year.

η Values used: Cline: $\eta = 1.5$; Nordhaus (1994) $\eta = 1$, DICE(2007) $\eta = 2$, RICE (2011) $\eta = 1.5$; Stern $\eta = 1$.

with $g = 1.3\%$

SDR: $r\,(\text{Cline}) = 2.05\%$, $r\,(\text{Nordhaus 1994}) = 4.3\%$,
$r\,(\text{Stern}) = 1.4\%$



Non CF countries	**G**	**e**	**P**	**SDR**
Austria	1.9	1.63	1.0	4.1
Denmark	1.9	1.28	1.1	3.5
France	2.0	1.26	0.9	3.4
Italy	1.3	1.79	1.0	3.3
Germany	1.3	1.61	1.0	3.1
Netherlands	1.3	1.44	0.9	2.8
Sweden	2.5	1.20	1.1	4.1
CF countries	**G**	**E**	**P**	**SDR**
Czech Rep.	3.5	1.31	1.1	5.7
Hungary	4.0	1.68	1.4	8.1
Poland	3.8	1.12	1.0	5.3
Slovakia	4.5	1.48	1.0	7.7

Source: European Commission (2014).

The SDR under Risk

When future consumption is uncertain, the SDR formula becomes

$$r_t = \rho - \frac{1}{t} \ln \left(\frac{\mathbb{E} U' \left(c \left(t \right) \right)}{U' \left(c \left(0 \right) \right)} \right).$$

If the logarithm of consumption follows a stationary Brownian motion

$$d \ln c_t = \mu dt + \sigma dz_t \text{ which implies } \frac{dc_t}{c_t} = \left(\mu + \frac{1}{2} \sigma^2 \right) dt + \sigma dz_t$$

where z_t is a Brownian motion. Then the Ramsey formula becomes (Gollier 2007):

$$r_t = \rho + \eta \mu - \frac{1}{2} \eta^2 \sigma^2 \tag{22}$$

Climate Change Adjustments and the Ramsey Rule

$$u(c,T)=\frac{\left(Ce^{-\gamma T}\right)^{1-\eta}}{1-\eta} \tag{23}$$

$$r=\rho+\eta\frac{\dot{C}}{C}-\gamma(\eta-1)\Lambda\dot{T} \tag{24}$$

$$r=\rho+\eta\frac{\dot{C}}{C}-\gamma(\eta-1)\Lambda E \tag{25}$$

$$r=\rho+\eta\frac{\dot{C}}{C}-\gamma(\eta-1)\beta\frac{\dot{S}}{S} \tag{26}$$

- Weitzman (2001) proved that computing the expected net present value (ENPV) of a project with an uncertain but constant discount rate is equivalent to computing the NPV with a certain but decreasing "certainty-equivalent" discount rate.
- Gamma discounting results in declining discount rates.

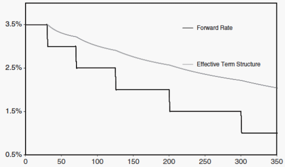


Figure 3 The UK government social discount rate term structure
Notes: The forward rate is the rate used to discount benefits and costs from year $t+1$ back to year t. The effective term structure gives the rate used to discount benefits and costs from year t back to year 0.
Source: HM Treasury (2003).

Figure: Declining SDRs

Source: HM Treasury 2001.

The Damage Function

- The damage function is a reduced form relationship linking damages to the economy with changes in temperature:

$$D_t = D(T_t) \tag{27}$$

where the temperature T can be regarded as an aggregate proxy of climate change.

- Two ways for introducing damages into the models of climate change and the economy.

1. Through the utility function that defines the welfare objective

$$U(C_t, T_t)\ , \frac{\partial U}{\partial C} > 0, \frac{\partial^2 U}{\partial C^2} < 0, \frac{\partial U}{\partial T} < 0 \tag{28}$$

2. Through a multiplicative term associated with the production function.

$$D(T_t)\left[F(A_t, K_t, L_t)\right]\ , D'(T_t) < 0 \tag{29}$$

where $F(A, K, L)$ is a standard production function

Damages in the Utility Function: Specifications

$$U(C,T) = u(C) - D(T) \tag{30}$$

$$U(C,T) = \frac{C^{1-\eta}}{1-\eta} - \mu \frac{T^{1-\sigma}}{1-\sigma} \quad \sigma \geq 1 \tag{31}$$

$$U(C,T) = \ln\left(Ce^{-\gamma T}\right) = \ln C - \gamma T \tag{32}$$

$$U(C,T) = \frac{\left(Ce^{-\gamma T}\right)^{1-\eta}}{1-\eta} \tag{33}$$

CES utility : $(C,T) = \frac{1}{1-\gamma}\left[(1-\delta)\, C^{\frac{\sigma-1}{\sigma}} + \delta Q^{\frac{\sigma-1}{\sigma}}\right]^{\frac{(1-\gamma)\sigma}{\sigma-1}}$

$$Q = \frac{1}{1+\alpha T^2}$$

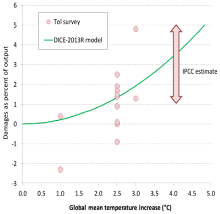
Damages in the Production Function: Specifications

$$\begin{array}{cc}
\text{RICE-96} & D(T_t) = 1 - \frac{1}{1+\theta_{1,i}\left(\frac{T_t}{3}\right)^{\theta_2}} \quad i = 1, \ldots, 12 \text{ regions} \\
\text{RICE-99} & D(T_t) = 1 - \frac{1}{1+\theta_{1,i}T_t+\theta_{2,i}T_t^2} \\
 & D_t = f_1\left[T_t\right] + f_2\left[SLR_t\right] + f_3\left[S_t\right] \approx \theta_1 T_t + \theta_2 T_t^2 \\
\text{RICE-2011} & \theta_1 = 0.0018\ ,\ \theta_2 = 0.0023 \\
 & \Omega_t = \frac{D_t}{1+D_t} \\
\text{DICE-2013R} & D(T_t) = 1 - \frac{1}{1-0.00267T^2} \approx 0.023\left(\frac{T_t}{3}\right)^2
\end{array}$$

Output net of damages is:

$$Y = \left(1 - D\left(T\right)\right) F\left(K, L, A, E\right) \tag{34}$$

$$D\left(T\left(S\right)\right) \approx 1 - \mathrm{e}^{-\gamma\left(S(t)-S_0\right)}\ ,\ \frac{1}{1-D}\frac{\partial D\left(T\left(S\right)\right)}{\partial S} = \gamma = \frac{5.3}{10^5}$$



Climate change cost

Source: DICE-2013R

- Pindyck (2017) criticizes the IAMs and the use of damage functions by pointing out that "when it comes to the damage function, we know virtually nothing – there is no theory and no data that we can draw from.
- Pindyck suggests that the focus should be on damages related to catastrophic outcomes. Temperature increases larger that 5°C.

- Dell et al. (2014) consider a DICE-type damage function and output specifications:

$$\Omega(T) = \frac{1}{1+\pi_1 T + \pi_2 T^2} \quad (35)$$

$$Y_t = \Omega(T) A_t F(K_t, L_t) \quad (36)$$

where as $A_t F(K_t, L_t)$ is potential output in the absence of climate change damages. A process linking the evolution of productivity with climate change damages is:

$$\log A_t = \log A_{t-1} + D(T) \quad (37)$$

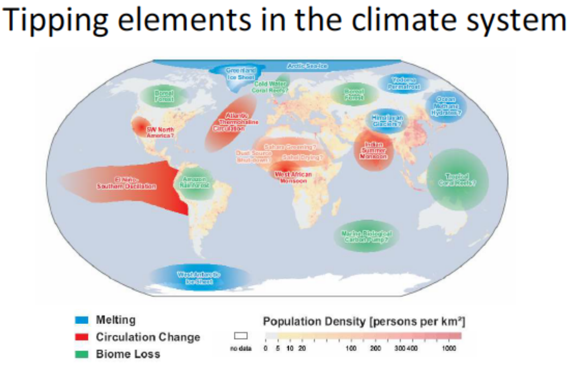
$$Y_t = A_t F(K_t, L_t) \quad (38)$$

where $D(T)$ is a damage function.

- Results obtained by using distributed lag models (Dell et al. 2012) suggests that for poor countries, temperature shocks appear to have long-lasting effects;

Tipping Points

Uncertainty and "tipping points". Points where a small forcing is enough to set of a chain of interactions causing a major change in behavior of the system (Roe and Baker, 2010).



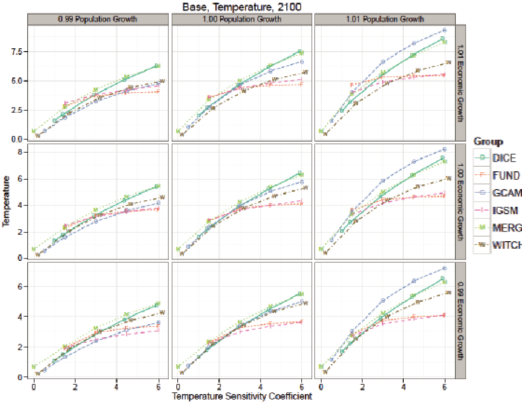
Source: Updated from Lenton (2008).

Uncertainty and IAMs

The main sources of uncertainty include: (Gillingham et al. 2015).

1. parametric uncertainty, such as uncertainty about climate sensitivity or output growth;
2. model or specification uncertainty, such as the specification of the aggregate production function or the damage function;
3. measurement error, such as the level and trend of global temperatures;
4. algorithmic errors resulting in an incorrect solution to a model;
5. random error in structural equations, such as those due to weather shocks;
6. coding errors in writing the program for the model; and
7. scientific uncertainty or error, such as when a model contains an erroneous theory.

Responses of IAMs solution paths to changes in parameters.



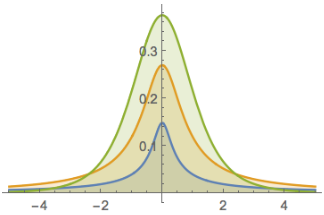
Source: Gillingham et al. (2015)

A tail event can be regarded as an extreme event which occurs outside the range of what is normally expected.

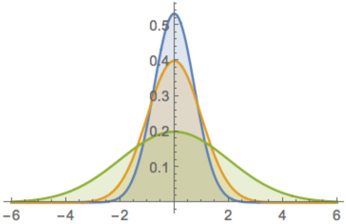
Definition

A thin-tailed distribution has a finite upper limit (such as the uniform distribution), a medium-tailed distribution has exponentially declining tails (such as the normal distribution), and a fat-tailed distribution has power law tails (such as the Pareto distribution or Student-t).

The Student-t Distribution



The Normal Distribution



Fat-tailed Distributions and the Dismal Theorem in Climate Change

Weitzman (2009) has proposed what he calls a dismal theorem. He summarizes the theorem as follows:

> *The catastrophe-insurance aspect of such a fat-tailed unlimited-exposure situation, which can never be fully learned away, can dominate the social-discounting aspect, the pure-risk aspect, and the consumption-smoothing aspect.*

Theorem

The amount of present consumption the agent would be willing to give up in the present period to obtain one extra sure unit of consumption in the future period is infinite if the probability density of uncertain future consumption is fat tailed.

- The gradualist policy ramp (DICE, RICE) means that carbon taxes start at low levels and increase with time, which is the "gradualist approach" to climate policy.

Corollary

Qualitatively, fat tails favor more aggressive policies to lower GHGs than the "standard" CBA. This can be considered as an important reason to take significant action now, instead of the action implied by the gradualist policy ramp, This a different reason for taking action now than the near zero rate of pure time preference.

- Since the mid-20th century, economic theory has been dominated by the Bayesian paradigm, which holds that any source of uncertainty can and should be quantified probabilistically. The standard line of reasoning of the Bayesian approach is that, in the absence of objective probabilities, the DM should have her own subjective probabilities, and that these probabilities should guide her decisions.
- However, Knight (1921) and Keynes (1921, 1937) argued that not all sources of uncertainty can be probabilistically quantified. Knight suggested distinguishing between "**risk**", referring to situations described by known or calculable probabilities, and "**uncertainty**", where probabilities are neither given nor computable.

- Gilboa and Schmeidler (1989) extended decision making under uncertainty by incorporating ambiguity and by moving away from the framework of *expected utility* maximization.
- They adopted a **maxmin expected** utility framework where the DM optimizes over the worst-case outcome (i.e., the worst-case prior) that may conceivably come to pass.

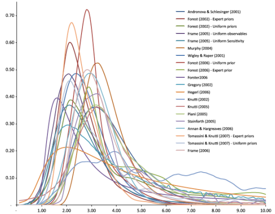


Fig. 1 Estimated probability density functions for climate sensitivity from a variety of published studies, collated by Meinshausen et al. (2009)

Source: Meinshausen et al. (2009)

Motivated by concerns about model misspecification in macroeconomics, Hansen and Sargent (2001a,b, 2008, 2012) and Hansen et al. (2006) extended Gilboa and Schmeidler's insights into dynamic optimization problems, thus introducing the concept of robust control to economic environments.

Robust Control and Climate Change

Assuming that deep uncertainty is related to the evolution of the stock of GHGs a robust control problem can be written (see Athanassoglou and Xepapadeas , 2012) as the constraint control problem .

$$\max_{E}\min_{h}\mathbb{E}\int_0^{\infty} e^{-\rho t}\left[aE-\frac{b}{2}E^2-\frac{\gamma}{2}\left(S-S_0\right)^2\right]dt$$

subject to

$$dS\left(t\right)=\left(mS_0+E-mS+\sigma h\right)dt+\sigma dB\ ,\ \ S\left(0\right)=S_0$$

$$\int_0^{+\infty} e^{-\delta t}\mathbb{E}_Q[\frac{1}{2}h_t^2]dt\leq\eta.$$

or the multiplier problem

$$\max_{E}\min_{h}\mathbb{E}\int_0^{\infty} e^{-\rho t}\left[aE-\frac{b}{2}E^2-\frac{\gamma}{2}\left(S-S_0\right)^2+\frac{\theta}{2}h^2\right]dt$$

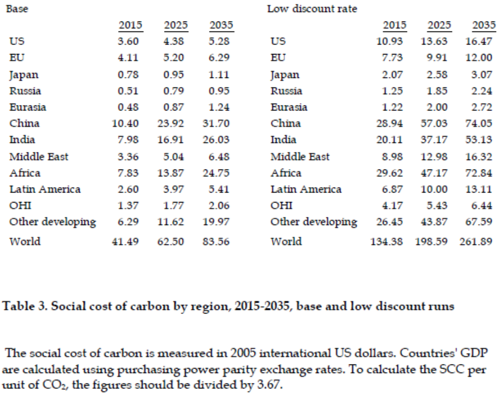
subject to distorted stock dynamics

- Smooth ambiguity (Klibanoff et al. 2005) provides a preference representation that separates tastes from beliefs, and allows us to parameterize attitudes to ambiguity via a differentiable function, in a manner analogous to the way utility functions represent risk preferences.
- By introducing the smooth ambiguity framework into the DICE model Millner et al. (2013) obtain results suggesting that for policy-relevant exogenous mitigation policies, the value of emissions abatement increases as ambiguity aversion increases, and that this 'ambiguity premium' can in some plausible cases be very large.

The RICE model is a regionalized version of the DICE model. It divides the world into 12 regions. These are US, EU, Japan, Russia, Eurasia (Eastern Europe and several former Soviet Republics), China, India, Middle East, Sub-Saharan Africa, Latin America, Other high income countries, and Other developing countries. The general structure of the RICE model is similar to the DICE model with disaggregation into regions.

$$W = \sum_{t=1}^{T_{\max}} \sum_{i=1}^{N} \psi_{i,t} U^i \left[c^i (t), L^i (t) \right] \frac{1}{(1+\rho)^t} \tag{39}$$

where $\psi_{i,t}$ are "Negishi weights" on each region and each time period.



Base

	2015	2025	2035
US	3.60	4.38	5.28
EU	4.11	5.20	6.29
Japan	0.78	0.95	1.11
Russia	0.51	0.79	0.95
Eurasia	0.48	0.87	1.24
China	10.40	23.92	31.70
India	7.98	16.91	26.03
Middle East	3.36	5.04	6.48
Africa	7.83	13.87	24.75
Latin America	2.60	3.97	5.41
OHI	1.37	1.77	2.06
Other developing	6.29	11.62	19.97
World	41.49	62.50	83.56

Low discount rate

	2015	2025	2035
US	10.93	13.63	16.47
EU	7.73	9.91	12.00
Japan	2.07	2.58	3.07
Russia	1.25	1.85	2.24
Eurasia	1.22	2.00	2.72
China	28.94	57.03	74.05
India	20.11	37.17	53.13
Middle East	8.98	12.98	16.32
Africa	29.62	47.17	72.84
Latin America	6.87	10.00	13.11
OHI	4.17	5.43	6.44
Other developing	26.45	43.87	67.59
World	134.38	198.59	261.89

Table 3. Social cost of carbon by region, 2015-2035, base and low discount runs

The social cost of carbon is measured in 2005 international US dollars. Countries' GDP are calculated using purchasing power parity exchange rates. To calculate the SCC per unit of CO_2, the figures should be divided by 3.67.

The impact of climate change is expected to vary profoundly among geographical locations in terms of temperature and damage differentials. The spatial dimension of damages can be associated with two main factors:

- Natural mechanisms which produce a spatially *non-uniform* distribution of the surface temperature across the globe.
- Economic-related forces which determine the damages that a regional (or local) economy is expected to suffer from a given increase in the local temperature.
- However, natural mechanisms related to the fact that the energy flows vary with latitude and over the year producing differences in temperatures over space and time are not taken into account by standard IAMs.

Statistical downscaling, referred also as pattern scaling is a method which allows for the approximation of local temperature using data on global average temperature and initial values of local temperature. (Hassler, Krussel and Smith 2016, Desmet and Rossi-Hansberg 2015)

- One-dimensional EBCMs are describing spatial temperature heterogeneity caused by heat transportation, or flux, across space. The basic energy balance equation developed by North (1975a, equation (29)), with human input added, can be written as:

$$\begin{aligned}\frac{\partial T(x,t)}{\partial t} &= QS(x)\alpha(x,x_s(t)) - [I(x,t) - F_h(x,t)] \qquad (40)\\ &\quad D\frac{\partial}{\partial x}\left[(1-x^2)\frac{\partial T(x,t)}{\partial x}\right],\end{aligned}$$

  where $x = 0$ denotes the Equator, $x = 1$ denotes the North Pole, and $x = -1$ denotes the South Pole.

- The use of one-D models in economic-climate modeling provides new results for that spatial distribution of damages and policies but introduces technical difficulties because of the need to use partial differential equations as constraints (Brock,Engstrom and Xepapadeas, 2014)

- The two-box energy balance model introduced by Langen and Alexeev (2007) and Alexeev and Jackson (2012) consists of a single hemisphere with two boxes or regions divided by the 30th latitude.

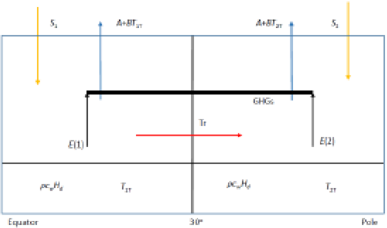


Figure 1: The two-box energy balance model

- One-dimensional EBCMs and two-box climate model have been used to study damages associated with polar amplification (PA), which is a well established scientific phenomenon which could generate significant climate damages.

- Theoretical Approach
- Noncooperative Games
- Cooperative Games
- Farsighted Games
- Asymmetric Countries, Transfers and Issue Linkages
- History of Climate Negotiations
- Paris Agreement

To successfully address climate change requires international collaboration. In the absence of a supranational authority that could enforce compliance, sovereign countries negotiate the terms and their participation in an International Environmental Agreement (IEA) based on their individual benefit and cost functions.

Assumptions of the basic model: countries make choices based only on their level of emissions,.no transfers or linkages to other issues are considered, only a single coalition is allowed and countries are symmetric. There are three main stands in the literature:

Three Main Approaches

1. Noncooperative games (Carraro and Siniscalco, 1993, Barrett, 1994 and Diamantoudi and Sartzetakis, 2006).
2. Cooperative games (Murdoch and Sandler, 1997).
3. Farsighted behavior (Diamantoudi and Sartzetakis, 2015; 2017)

- Each country i decides whether to participate in an agreement to reduce emissions and the level of its emissions by maximizing its social welfare of w_i, expressed as the net between benefits and damages:

$$w_i = B(e_i) - D\left(\sum_{i \in N} e_i\right).$$

- In order to determine the size of the stable IEA, the internal and external stability conditions should be satisfied.
- The noncooperative approach leads to the **grim result** the maximum number of countries joining a coalition is 4.
- The assumption driving the grim result is that when one country decides to leave the coalition, it assumes that no other country will follow and although the remaining coalition countries adjust their emission level the free riding incentives are strong.

- The core concept of stability is applied to coalition formation (Chander and Tulkens, 1995 and 1997).
- The cooperative approach asserts the formation of the grand coalition and the attainment of efficiency, assuming that when a country deviates it expects that the agreement collapses and each country fends for itself.
- Thus, full cooperation and social optimality are possible.

- The concept of farsighted stability has been used to bridge the gap between the polar assumptions of non-cooperative and cooperative games.
- Farsighted stability allows a potentially defecting country to take into account the fact that its choice will affect the membership decisions of other countries and not only their choice of emissions.
- The advantage of farsighted stability is that it considers what happens after an initial deviation in a consistent manner, in accordance with individual optimization behavior and not based on apriori assumptions.

- Diamantoudi and Sartzetakis (2017) show that larger coalitions are farsighted stable, relative to the myopic one and they yield substantially lower aggregate emission levels and higher aggregate welfare levels.
- Therefore, the assumption of farsighted countries allows for larger coalitions relative to the myopic behavior.
- Although the grand coalition does not necessarily belong to the set of stable coalitions, it is a possible equilibrium outcome.

- Results of the theoretical literature introducing asymmetry are mixed: some papers support the idea that the introduction of heterogeneity yields larger stable coalitions, with and without transfers, while some others find that transfers are necessary to induce larger stable coalitions. Allowing the formation of separate coalitions could improve welfare and environmental quality.
- Allowing for transfer payments, especially when they are made conditional on total emissions, improves the size of the coalition and the grand coalition can be a stable outcome. Some papers find that the only effective transfers are those among coalition members that ensure internal stability.

- Some papers suggest to link the environmental game, in which signatories cannot exclude nonsignatories from enjoying the benefits that the coalition generates, to a club good game where exclusion from enjoying the club benefits is possible. Three proposals:
  - link IEAs with trade negotiations,
  - linking IEAs with Research and Development (R&D) cooperation,
  - introducing reputation effects.
- Most papers find that the coalition could be enlarged though issue linkages.

- **Can the incidence of the recent withdrawal of the USA from the Paris agreement be analyzed in terms of the above approaches ?**

- Leading to Kyoto:
  - 1979. First World Climate Conference organized in Geneva by the World Meteorological Organization (WMO).
  - 1988. The Intergovernmental Panel on Climate Change (IPCC) was established.
  - 1992. The UN Framework Convention on Climate Change (UNFCC) was created.
  - 1995. The first Conference of the Parties (COP 1) took place in Berlin.
  - 1997. The Kyoto Protocol was formally adopted at COP 3 and went into effect in 2005. First commitment period started in 2008 and ended in 2012, while the second began on 1 January 2013 and ends in 2020.

- Post Kyoto:
  - 2007. COP 13 (the Bali Action Plan) started negotiations for the post Kyoto agreement.
  - 2009. COP15 in Copenhagen (Copenhagen Accord) initiated the move from individual country targets (such as those set in the Kyoto Protocol) to national emissions limitation pledges.
  - 2012. COP 18 in Doha reached an agreement to extend the life of the Kyoto Protocol until 2020.
  - 2015. COP 21 in Paris. The Paris Agreement brought 195 nations under one framework to set the target of limiting global temperature increase to "well below 2°C", by providing the necessary flexibility in the same time that maintains several aspects of the agreement as legally binding.

- The Paris Agreement entered into force on 4 November 2016, after the ratification threshold of at least 55 Parties to the Convention accounting in total for at least an estimated 55 % of the total global GHG emissions was achieved.
- Today, 147 out of the 197 Parties to the Convention have ratified the Agreement.
- The first session of the Conference of the Parties serving as the Meeting of the Parties to the Paris Agreement (CMA 1) took place in Marrakech, Morocco in November 2016.

- Main achievements:
  - while there are no legally binding targets for individual countries, the monitoring and reporting process is binding,
  - allowing for flexibility made possible the agreement of the developing countries,
- Main characteristics:
  - recognizes the importance of averting, minimizing and addressing loss and damage associated with the adverse effects of climate change,
  - includes elements of financial support especially towards the Least Developed Countries,
  - re-introduces carbon markets by providing the opportunity to expand the reach of carbon pricing to enable implementation of NDCs.

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- In terms of theory it combines micro and macroeconomics with climate science, with the purpose of designing efficient policies to correct for the mother of all externalities.
- It is interdisciplinary in nature and combines very important aspects of both economics and climate science.
- In terms of applied policy it is important since it helps designing instruments for addressing an issue that may have catastrophic consequences for future generations.

The purpose of this presentation was twofold:

1. To provide a review of the current state of the art in the economics of climate change.

Climate change and monetary policy is an area where very little research has been undertaken and our approach seeks to explore ways that monetary policy can help in the design of efficient climate policies.

The purpose of this presentation was twofold:

1. To provide a review of the current state of the art in the economics of climate change.
2. To suggest that economics of climate change could be extended to monetary policy.

Climate change and monetary policy is an area where very little research has been undertaken and our approach seeks to explore ways that monetary policy can help in the design of efficient climate policies.

- In the spirit of the new environmental macroeconomics we will develop a DSGE model with the structure of an integrated assessment model (IAM) in the sense that it will include two interacting modules the economy and the climate.
- In this DSGE model, except for the government which will be responsible for the design and implementation of fiscal and climate policies, there will also be a Central Bank which will have its own objectives and will decide on the design and implementation of monetary policymaking.

- Temperature dynamics and the structure of the model will be based on the structures discussed and presented before.
- In this context the Central Bank could use the money stock or the market nominal interest rate to affect and stabilize the macroeconomy, stabilize emissions, help design efficient adaptation strategies to mitigate the consequences of climate change.
- Thus, the main challenge will be to investigate the properties of Central Bank behavior and monetary policy under climate change and global warming.

- To give a real role to monetary policy, namely to make money matter to real variables, we will follow the New-Keynesian tradition, and thus assume that product markets are not perfectly competitive and prices are sticky at least temporarily.
- We will work with feedback policy rules, and we will try to introduce new concepts like the environmentally adjusted output gap.

- The developed model will be calibrated to the US and/or Eurozone.
- We will explore the ways that environmental risks, in the form of shocks, and policy reactions to counter these shocks, affect the real economic activity and the environment.
- Which monetary policy reactions are really stabilizing and which constitute unnecessary intervention?
- What are the tradeoffs or social dilemmas faced?
    - Does a better environment come at the cost of growth and employment, or can we find policy mixes that can promote both? Are there complementarities between various policies?
- Can monetary policy promote adaptation, international cooperation and stable environmental agreements?

- We will use the above model and techniques to study the Greek economy. The basic characteristic here is that greenhouse gas emissions emanating from Greece are very small relative to the world emissions to seriously affect global climate change or global warming.
- There is however a very important reverse relationship, since it is global warming and climate change that evolves exogenously relative to the actions of Greece that may have serious negative effect on the Greek economy (see The Study of the Bank of Greece).
- We will explore whether there is space for interventions on the part of monetary authorities in order to mitigate these negative effects.

- Extensions to the basic model, which go beyond the time frame and the deliverables of the current project, could be directed towards addressing issues emerging from Pindyck's critique, and focusing on climate change policy, including monetary policy, under deep uncertainty or ambiguity.