THE ECONOMICS OF CLIMATE CHANGE

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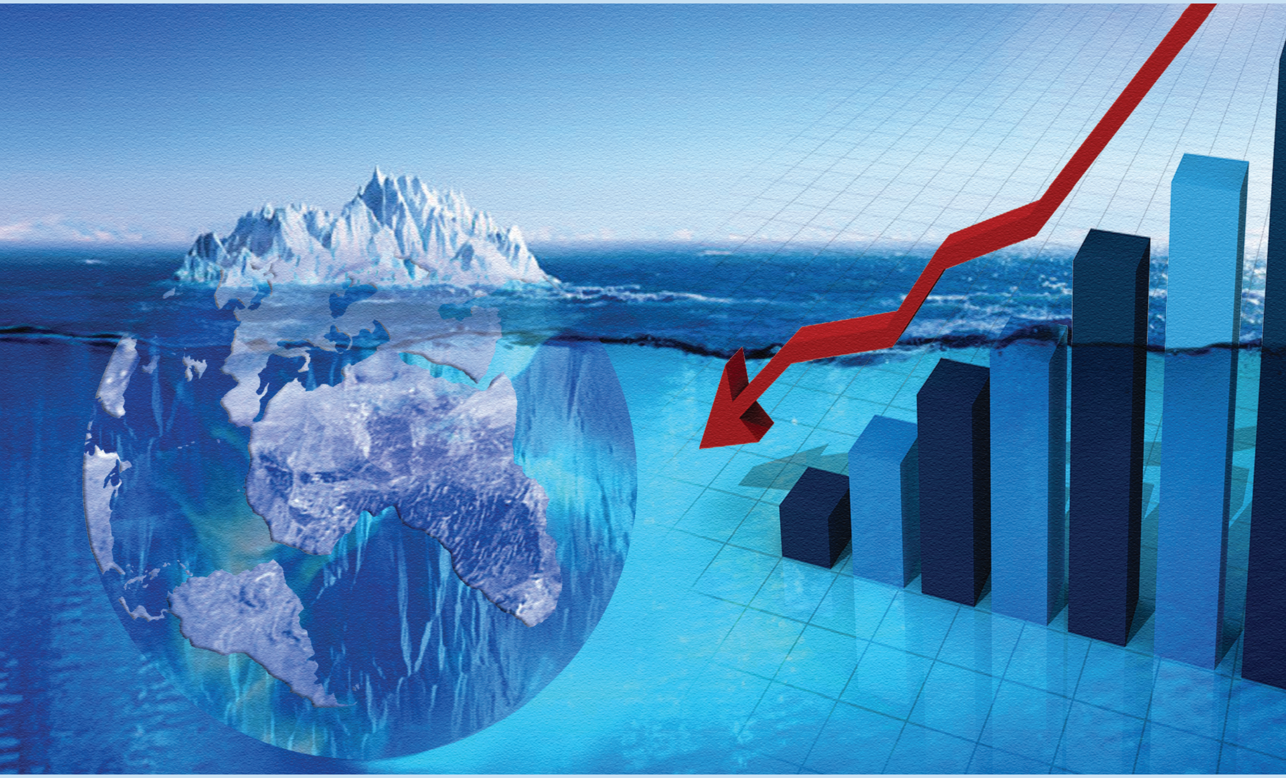
EFTICHIOS SARTZETAKIS AND ANASTASIOS XEPAPADEAS



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The Economics of Climate Change

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Foreword

Climate change is gradually shaping a new environment for economic policy making. Research thus far confirms that the current and projected implications of climate change for the society and for sustainable development are such that we cannot continue with the "business as usual" scenario. We need to mitigate and shift to a lower-carbon economy, but also manage risks and adapt to the changing climate.

In this process, it is crucial to create the conditions for well-informed and far-sighted decisions that address risks and opportunities resulting from the changing climate. This is why, during the past decade, the Bank of Greece has been studying issues related to climate change and why we intend to continue to do so.

The present volume provides a comprehensive, state-of-the-art review of the economics of climate change, focusing on the design of economic policy aimed at controlling the climate externality. It begins with a presentation of the modeling of the climate, the way in which the climate and the economy are modeled as a coupled system, and a literature review of the emerging area of environmental macroeconomics. There follows an overview of mitigation-related climate change policies, such as proposals for carbon taxes and cap-and trade policies, along with an analysis of the economics of private and public adaptation which includes both adaptation policies and adaptation finance.

The volume also discusses discounting for the future and the associated concerns about the welfare of future generations. It addresses the way in which climate change damages are estimated, and the impacts of risk and uncertainty –which are inherent in climate change analysis– on policy design.

Climate change –which is a global problem– affects all countries, both large and small. In recognition of this fact, the international community has undertaken internationally agreed-upon policies, such as the Kyoto Protocol and the more recent Paris Accord, in order to address the problem on a global level. This volume presents the theoretical foundations of environmental agreements and also traces the history of these agreements and the international agencies created to implement and support them.

Historically, climate change can be attributed primarily to the actions of the large, industrialized countries. However, its impacts are diffused to small as well as large countries. Greece, as a small country in the climate-sensitive Mediterranean region, is expected to incur adverse effects from climate change. However, the adoption of policies and technologies leading to a low-carbon Greece, and the implementation of efficient adaptation programs, could provide a very promising opportunity for Greece to boost its development and increase its competitiveness in the international arena, while at the same time implementing the climate policies agreed upon by the international community.

Currently, there is a debate on whether monetary policy and macroprudential tools should be used by central banks and financial regulators to enhance green finance and facilitate the transition to a lower-carbon economy, avoiding any destabilization effects. The focus of central banks is on inflation and financial stability, yet –given the magnitude of the sustainability challenges we currently face– I believe we should investigate the potential for central banks and regulators to revisit their role in the light of climate change.

This volume, apart from a review of the state-of-the-art of the economics of climate change, also sets the foundations for addressing the role of monetary policy under conditions of global warming and exploring the link between monetary policy and climate change.

Yannis Stournaras
Governor of the Bank of Greece
Athens, June 2018

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Abbreviations

Below is a list of selected abbreviations that appear in this volume.

AR:	Assessment Report
CaT:	California's Cap-and-Trade program
CBA:	cost-benefit analysis
CDM:	Clean Development Mechanism
CER:	Certified Emission Reduction
CGE:	computable general equilibrium
CO_2:	carbon dioxide
COP:	Conference of the Parties
CRI:	consumption rate of interest
DDR:	declining discount rate
DE:	decentralized equilibrium
DICE:	Dynamic Integrated model of Climate and the Economy
DSGE:	dynamic stochastic general equilibrium
EBCM:	energy balance climate model
ERU:	Emission Reduction Unit
ETS:	emissions trading scheme
EU ETS:	European Union Emissions Trading System
EUA:	European Union allowance
FUND:	Climate Framework for Uncertainty, Negotiation, and Distribution
GCAM:	Global Change Assessment Model
GDP:	gross domestic product
GHG:	greenhouse gas
IAM:	integrated assessment model
IEA:	international environmental agreement
IGSM:	Integrated Global Systems Model
IPCC:	Inter-governmental Panel on Climate Change
JI:	joint implementation
MAGICC:	Model for the Assessment of Greenhouse-Gas Induced Climate Change
MERGE:	Model for Evaluating Regional and Global Effects of greenhouse gas reduction policies
NDC:	nationally determined contribution
NPV:	net present value
PAGE:	Policy Analysis of the Greenhouse Effect
PES:	payments for environmental service
R&D:	research and development

RBC: real business cycle
RCP: representative concentration pathway
REDD+: Reducing emissions from deforestation and forest degradation, and enhancing forest carbon stocks in developing countries
RGGI: Regional Greenhouse Gas Initiative
RICE: Regional Dynamic Integrated model of Climate and the Economy
SCC: social cost of carbon
SDR: social discount rate
STP: social time preference
TCRE: transient carbon response parameter
TFP: total factor productivity
UNFCCC: United Nations Framework Convention on Climate Change
WITCH: World Induced Technical Change Hybrid

1 Introduction

There is an extensive and well-documented body of scientific evidence suggesting that global warming is the result of human activities associated with the use of fossil fuels and the emissions of carbon dioxide and other greenhouse gases (GHGs). Although there are many uncertainties, the scientific consensus is that a business-as-usual scenario might have serious negative impacts on human wellbeing. It has been pointed out (see, for example, Nordhaus, 2007, Stern, 2008) that:

- Under business as usual, over the next two centuries we are likely to see change in climate at a very fast rate and on a scale that the world has not experienced in recent history.
- Science provides indications that the probability and frequency of floods, storms, droughts and so on is likely to continue to grow with cumulative emissions of GHGs, and that the magnitude of some of these impacts could be irreversible and/or catastrophic.
- The objective of climate change economics is to use climate science and the projected evolution of climate under the impact of anthropogenic GHG emissions in order to design economic policies which will prevent or minimize undesirable events.

In terms of economic analysis, climate change is an externality. Environmental and resource economics has long been associated with the concepts of externalities and market failure. It is well known, of course, that 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:

- It is global in its impacts. GHG emissions generated in a certain location have impacts which are spread all over the planet, with different geographical intensities.
- Reducing emissions is an extreme global public good. All nations share the benefits from reduced emissions, while the nations that reduce emissions bear

the cost of reduction. This generates free-riding incentives.

- Some of the effects are very long term and governed by nonlinear dynamics with positive feedbacks.

The standard economic theory of externalities suggests that the resulting market failure can be corrected using standard policy instruments. These include Pigouvian taxes, or allocation of property rights through some kind of bargaining (the Coasian approach).

In the case of climate change, although economic policy design follows these basic lines, it must take into account a very large number of economic considerations such as: estimating damages from climate change; dealing with deep uncertainty; characterizing impacts on growth, development and technical change; the need to formulate global policies in the absence of a supranational authority and under free-riding incentives; addressing intragenerational and intergenerational distribution, which raises important ethical issues between rich and poor nations and between present and future generations. Parallel to these economic issues, economic policy should take into account the evolution of climate and the dynamic interactions between the climate and the economy. This is undoubtedly a formidable task, which has contributed to a large and important scientific literature and many important applications at both the national and international levels.

In this context, the present volume aims to provide a comprehensive, state-of-the-art presentation of the economics of climate change with particular focus on the design of economic policy for controlling the climate externality. Furthermore, we set the foundations for addressing an important issue that has not been analyzed sufficiently in the economics of climate change, which is the role of monetary policy under conditions of global warming. It has been argued that climate change can affect growth both in terms of output levels and steady-state equilibrium output, and also in terms of output growth through impacts on total factor productivity. Economic policy to reduce negative impacts though instruments such as carbon taxes may also change relative prices and the general price level. This situation imposes new challenges on central banks, in addition to their traditional role of inflation and output stabilization. Monetary policy needs to take into account the fact that output and the output gap are affected by global warming, and that relative prices – and possibly the general price level – might be affected by other climate change policies, such as the introduction of carbon taxes, cap-and-trade policies or adaptation policies. Other important issues related to central bank operations under climate change conditions are associated with the valuation of climate risks, the treatment and the impacts of stranded assets, the potential differentiation of capital requirements between 'green' and 'brown' assets, the correct pricing of assets when climate change impacts are internalized, and the adoption of 'green' quantitative easing policies.

As far as we know, systematic research has not been undertaken toward this goal, and our intuition is that monetary policy could play an important role in helping to design efficient climate change policies. Thus, a main research contribution of the present volume – in addition to providing a comprehensive survey of the evolution of climate change economics up to the present time – is to set the foundations for bringing the central bank and monetary policy into the economics of climate change as an additional tool for designing climate change policy.

Chapter 2 presents the modeling of climate in the period after the industrial revolution, that is, during the period of anthropogenic influence. This is necessary for the development of coupled models of the economy and climate because it provides the link and the interactions between them. Modeling the climate also provides the parameters which are necessary for the calibrations which result in policy outputs, such as desired emission paths, the social cost of carbon, carbon taxes and cap-and-trade policies.

Chapter 3 presents the way in which the economy and climate are modeled as coupled systems. We start by presenting dynamic stochastic general equilibrium (DSGE) models of the economy, because these models will be our main vehicle for studying monetary policy under climate change. Then we present the integrated assessment models (IAMs) which have been the main tool for modeling the economy and climate and for deriving the main policies. We present analytically the most widely-used IAM, the Dynamic Integrated model of Climate and the Economy (DICE) model. Then we review the new literature which focuses on environmental macroeconomics. This literature combines low-dimensional DSGE models with climate change externalities, but without incorporating the central bank.

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 4 includes an analysis of carbon budgeting, the social cost of carbon, and carbon taxes, along with a brief presentation of carbon capture and storage, and deforestation reducing policies (REDD+). Chapter 5 analyzes the theoretical foundations of cap-and-trade policies, discusses issues of efficiency and market power, and presents existing and emerging emissions trading systems, along with a presentation of the European Union Emissions Trading System (EU ETS).

Chapter 6 presents and analyzes adaptation. In particular the chapter discusses the economics of adaptation, private and public adaptation, adaptation instruments and finance.

Chapter 7 addresses some of the most important structural elements of joint models of the economy and climate. These elements include discounting; the modeling of damages, risk and deep uncertainty; and regional issues, with the introduction of explicit spatiotemporal climate models.

Chapter 8 discusses international environmental policy and international agreements. It covers issues related to the theory of international agreements and coalition formation in the context of cooperative and non-cooperative game theory, the history of climate negotiations, and the recent Paris agreement.

Chapter 9 concludes and presents some promising areas of future research. Central among them is the development of DSGE IAM models with climate change externalities, which will enable the exploration of the link between monetary policy and climate change, and will provide new insights into the design of climate change policies.

1.1 References

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2 Modeling Climate after the Industrial Revolution

2.1 The natural system

The modeling of climate and the evolution of temperature is based on energy balance relationships between incoming and outgoing radiation. The incoming short-wave radiation is 340 W/m^2 when averaged over the surface of the earth. Approximately one-third of this is directly reflected back to space. In equilibrium, the resulting net short-wave radiation must be balanced by the outgoing long-wave radiation. At a pre-industrial equilibrium state, the incoming and outgoing energy fluxes were equal, and the global mean temperature was therefore constant on the average.

However, the post-industrial revolution period introduced an anthropogenic perturbation to the energy budget through the use of fossil fuels. This perturbation is usually denoted by F (measured in W/m^2) and is called **forcing**. Due to the perturbation, the incoming energy flux is larger than the outgoing flux, which leads to increasing temperature.

Under a perturbation $F(t)$, the evolution of global mean temperature can be described by

$$\frac{dT(t)}{dt} \equiv \dot{T}(t) = \sigma\left[F(t) - \kappa T(t)\right],\ T(0) = 0, \tag{2.1}$$

where $\dot{T}(t)$ denotes the increase in the global mean temperature, measured in degrees Celsius (°C), compared to the pre-industrial steady-state temperature $T(0)$. This is called the **temperature anomaly.** The forcing $F(t)$ is determined by the carbon dioxide (CO_2) concentration through the greenhouse effect. Parameter κ reflects the rate of outgoing infrared radiation to space with the empirical coefficient κ derived from satellite measurements.[1] Thus the term $\kappa T(t)$ describes the fact that a higher temperature leads to a larger outgoing energy flux and acts broadly as a depreciation term.

---

1 In more general spatial energy balance models, the outgoing radiation is approximated by Budyko's (1969) formula, $I = A + BT$ where the coefficients A,B are estimated by regression analysis.

The parameter σ determines how quickly the temperature changes as a result of a given imbalance in the fluxes, and is inversely proportional to the heat capacity of the climate system, which is dominated by the ocean. Assuming that F is constant, $F(t) = F$, the solution to equation (2.1) with the initial condition $T(0) = 0$, since at the pre-industrial state the anomaly is zero, is:

$$T(t) = \frac{F}{k}\left(1 - e^{-\sigma kt}\right),$$

with a steady state as $t \to \infty$: $T_\infty = \frac{F}{k}$.

Using the relationship between blackbody radiation and temperature, the value of κ is $\kappa = 3.2$ $\mathrm{Wm}^{-2}/$°C. This would imply that a perturbation of the energy balance by 1 Wm^{-2} increases the equilibrium temperature T_∞ by 0.3 °C. Sometimes this simple mechanism is referred to as the **Planck feedback**.

Due to various positive feedbacks, κ is likely to be smaller than this value, i.e., the outgoing energy flux increases less with increasing temperature than what is implied by the Planck feedback. In this case, a given forcing will result in a larger temperature increase. The earth's global average annual energy balance, based on the Kiehl and Trenberth (1997) study, is shown in Figure 2.1.

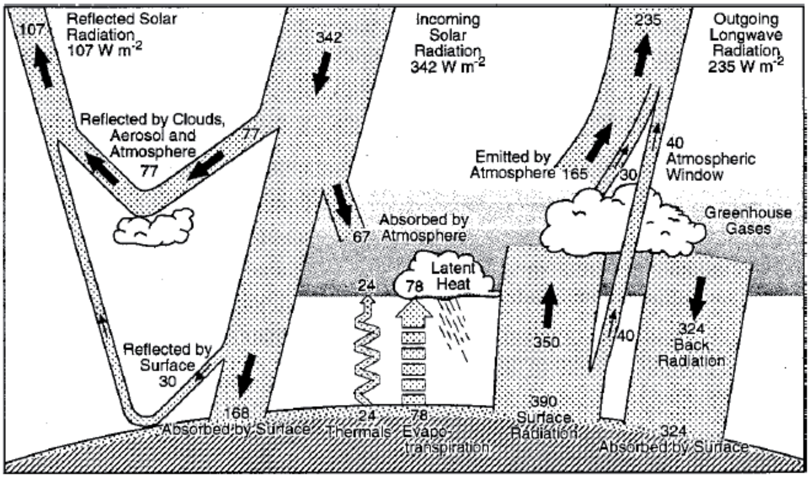

Figure 2.1. The earth's global mean energy budget

Source: Kiehl, J.T. and K.E. Trenberth (1997), "Earth's annual global mean energy budget", *Bulletin of the American Meteorological Society*, 78, 2, page 206, Figure 7. ©American Meteorological Society. Used with permission.

Greenhouse gases

Gases consisting of molecules with three or more atoms, such as CO_2, water vapor and methane, strongly absorb long-wave infrared radiation. Since the outflow of energy has a larger content of infrared radiation than does the inflow, an increase in the concentration of these gases has a strong positive effect on the energy balance. That is, it generates a positive forcing F. Gases with this property are called **greenhouse gases** or **GHGs**. Increases in the concentration of these gases have a large effect on the energy balance of the earth.

Carbon dioxide is the most important of the GHGs and its effect on the energy balance is approximated by the Arrhenius (1897) formula:

$$F = \frac{\eta}{\ln 2} \ln\left(\frac{S(t)}{S_0}\right), \tag{2.2}$$

where $S(t)$ and S_0 represent the current and pre-industrial atmospheric CO_2 concentrations, respectively. The appropriate values for this formula (see, for example, Schwartz et al., 2014, Hassler et al., 2016) are:

- Present concentration is 400 ppm; the pre-industrial value is $S_0 = 288$ ppm.
- $\eta \approx 3.7\ \mathrm{Wm}^{-2}$. This means that a doubling of the CO_2 concentration leads to the forcing $F = 3.7\ \mathrm{Wm}^{-2}$. Since the perturbation is related to the relative change in CO_2 concentration, the formula is valid regardless of the units used for the CO_2 concentration.
- We use the unit GtC, billions of tons of carbon in the atmosphere as a whole.
- The present value of $S \approx 840$ GtC, $S_0 \approx 600$ GtC.

Using (2.1) at the steady state $T_\infty = \frac{F}{k}$, and (2.2), we obtain:

$$T_\infty = \frac{\eta / \kappa}{\ln 2} \ln\left(\frac{S(t)}{S_0}\right),$$

The ratio η / κ is the heating that would arise in the steady state after a doubling of the CO_2 concentration. Using the Planck feedback gives $\eta / \kappa \approx 1.2$ °C. This is a modest sensitivity, and very likely too low of an estimate of the overall sensitivity of the global climate.

Positive feedbacks

A higher temperature will increase the atmospheric water vapor concentration, which adds to the forcing from CO_2. A higher temperature will also change the size of the global ice cover and cloud formation, both of which have an effect on the energy budget. More long-term feedbacks include additional GHGs from permafrost thawing. Assuming for simplicity linear feedbacks, we obtain:

$$\dot{T}(t)=\sigma\left[F(t)+\xi T(t)-\kappa T(t)\right].$$

In this case the steady-state temperature is given by:

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

The coefficient $\lambda = \eta/(\kappa-\xi)$ is called the **equilibrium climate sensitivity** and captures the response in the global mean temperature to a doubling of CO_2. The Intergovernmental Panel on Climate Change (IPCC, 2013) sets a likely range for λ of 3 °C ± 1.5 °C.

The link with the economy

The link between the climate and the economy is presented in Figure 2.2.

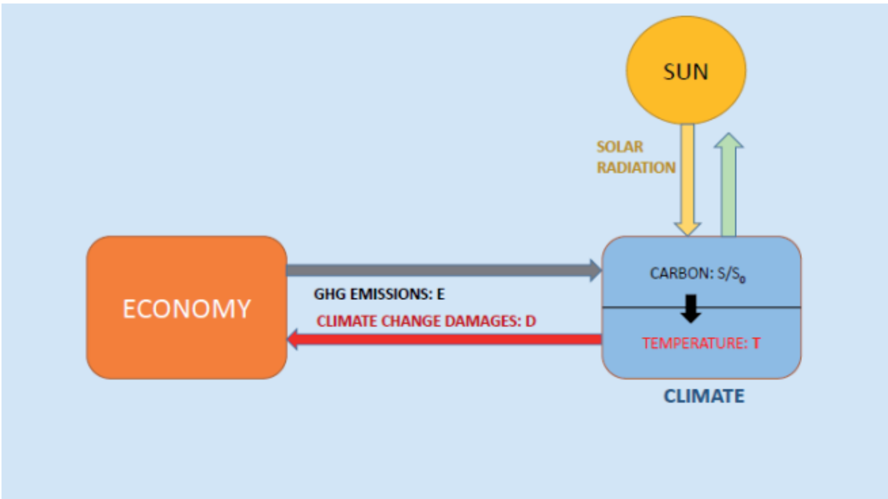

Figure 2.2. Climate and the economy

As indicated in Figure 2.2,

- The economy affects temperature and climate through emissions.

- GHG emissions E increase the actual atmospheric CO_2 (or GHGs) concentration relative to pre-industrial levels,

$$S_t - S_0 = \sum_{s=-T}^{t} E_s \left(1 - d_{t-s}\right),$$

where d_{t-v} is the carbon depreciation function, determined by the following facts:

    - one part (about 50 percent) of the emitted CO_2 leaves the atmosphere quite quickly (within a few years to a few decades),
    - another part (around 20–25 percent) stays for a very long time (thousands of years) until CO_2 acidification has been buffered,
    - the remainder decays with a half-life of a few centuries,
    - Golosov et al. (2014) represents this depreciation function by:

$$1 - d\left(s\right) = \varphi_L + \left(1 - \varphi_L\right)\varphi_0 \left(1 - \varphi\right)^{s/10},$$

    where $1 - d\left(s\right)$ describes the share of the emitted carbon that remains in the atmosphere after s units of time and the parameters $\left(\varphi_L, \varphi_0, \varphi\right) = \left(0.2, 0.38, 0.023\right)$ for s measured in years.

- In continuous time with a simple exponential temperature depreciation, the evolution of the stock of GHGs is given by:

$$\dot{S}\left(t\right) = E\left(t\right) - dS\left(t\right) \ , \ S\left(t\right) = S_0.$$

2.2 Climate–economy dynamics

The coupled dynamic system describing climate and its relation to the economy through GHG emissions, that is, the impact of GHG emissions on temperature, is given in continuous time by:

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

$$\delta = \xi - \kappa, \ \gamma = \sigma\eta, \ F_{EX} \ : \text{exogenous forcing}$$

$$\dot{S}\left(t\right) = E\left(t\right) - dS\left(t\right) \ , \ S\left(t\right) = S_0,$$

where ξ represents linear positive feedbacks. The coupled dynamics can be expanded by introducing the ocean temperature and taking into account that atmospheric temperature increases much faster than the ocean temperature. This implies that:

$$\dot{T}(t) = \frac{\gamma}{\ln 2}\ln\left(\frac{S}{S_0}\right) + F_{EX} + \delta T(t) - \sigma_2\left(T(t) - T^O(t)\right)$$

$$\dot{T}^O(t) = \sigma_3\left(T(t) - T^O(t)\right)$$

$$\delta = \xi - \kappa,\ \gamma = \sigma\eta,\ F_{EX}\ :\ \text{exogenous forcing}$$

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

where $T(t)$ and $T^O(t)$ respectively denote the atmospheric and ocean temperatures as deviations from the pre-industrial steady state. The temperature anomaly from 1850 to 2012 is presented in Figure 2.3.

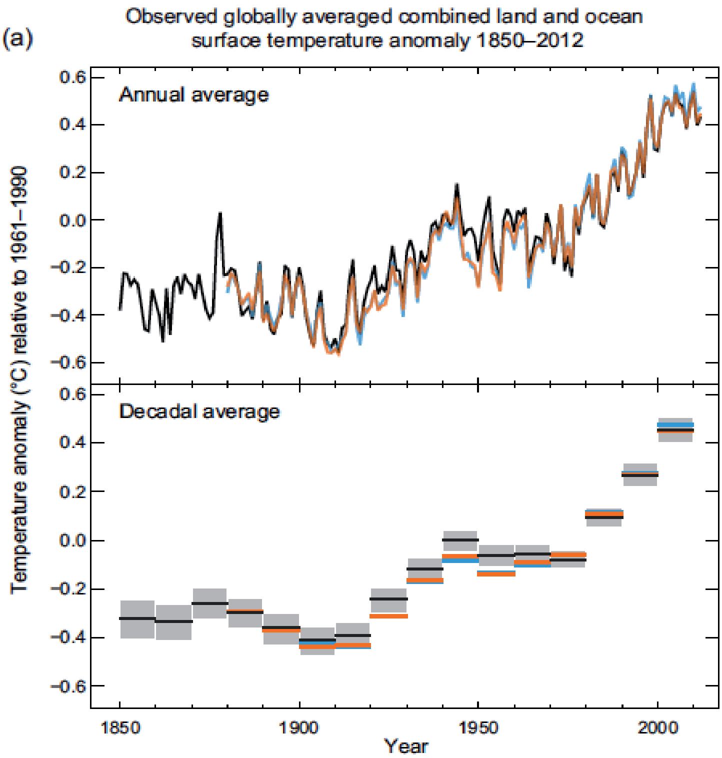

Figure 2.3. The temperature anomaly

Source: IPCC, 2013, *Climate Change 2013: The Physical Science Basis*, Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge, UK and New York, NY: Cambridge University Press, Figure SPM.1.

Figure 2.4 presents the path of global CO_2 emissions from 1870 to 2015, broken down by source of emissions, while Figure 2.5 shows the cumulative carbon budget for the same period.

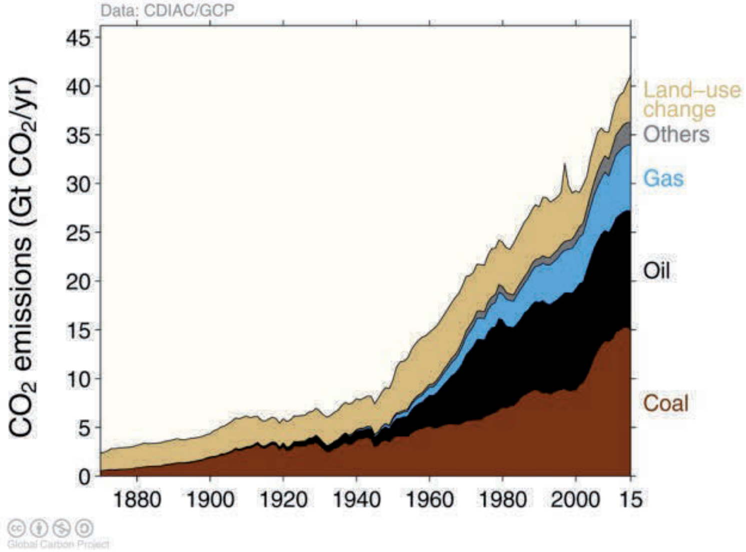

Figure 2.4. Global CO_2 emissions, by source

Note: Others – emissions from cement production and gas flaring.

Source: The Global Carbon Project, 2016. Reproduced under Creative Commons Attribution 3.0 License, available at https://creativecommons.org/licenses/by/3.0/.

In economic modeling, emissions can be expressed as a byproduct of output, which is determined by a standard production function, $Y = f(K, L)$. That is,

$$E(t) = g(Y),\ Y = f(K, L)$$

$$E(t) = s(t)\left[A(t)K(t)^{\alpha} L(t)^{1-\alpha}\right].$$

Alternately, emissions can be regarded as an input in the production function representing the use of fossil fuels, in which case

$$Y(t) = f(K, L, E)$$

$$Y(t) = A(t)K(t)^{\alpha} L(t)^{1-\beta} E(t)^{1-\alpha-\beta}.$$

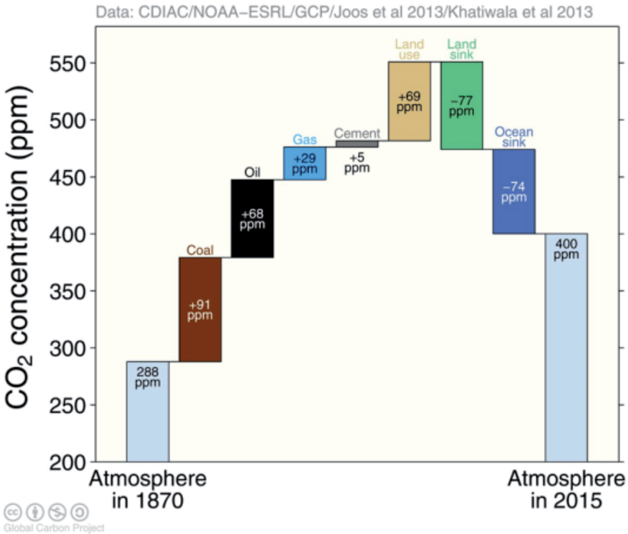

Figure 2.5. Cumulative contributions to the global carbon budget from 1870 to 2015

Source: The Global Carbon Project, 2016. Reproduced under Creative Commons Attribution 3.0 License, available at https://creativecommons.org/licenses/by/3.0/.

2.3 Cumulative emissions vs temperature: a linear relationship

Matthews et al. (2009), Matthews et al. (2012) and Leduc et al. (2016) suggested that:

1. The increase in mean global yearly temperature is approximately proportional to cumulative 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.

The constant of proportionality is called the **transient carbon response to emissions** (TCRE) parameter. This parameter is defined as the ratio of temperature change to cumulative carbon emissions, and is approximately independent of both the atmospheric CO_2 concentration and its rate of change over different time scales.

The TCRE is estimated to be in the range of 1.3–2.1 °C per trillion tons of carbon

(TtC) (or per 1000 PgC emitted). Under the proportionality assumption:

- A given emission of carbon will lead to an approximately constant increment to global temperature, regardless of when or over how long of a period this emission occurs.
- Uncertainty in the climate and carbon cycle response to emissions results in uncertainty in the temperature response to cumulative emissions.
- The long-term temperature change depends only on cumulative emissions, and not on the rate of change of emissions over the next century.
- The transient rate of warming does depend on the emissions scenario, with faster increases in cumulative emissions leading to faster rates of warming over the next few decades.
- The finding of approximate constancy of the carbon cycle response parameter allows a cumulative carbon budget to be set that should not be exceeded for a given threshold temperature, e.g., 2 °C.

The linear model has been derived and verified over the relevant range of emissions by MacDougal and Friedlingstein (2015), with the TCRE defined as:

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

where $\Delta T(t)$ is change in global average temperature up to time t, and $CE(t)$ is cumulative carbon emissions up to time t.

The linear relationship has also been recognized by the IPCC (2013, p. 1113), which stated that:

> In conclusion, taking into account the available information from multiple lines of evidence (observations, models and process understanding), the near linear relationship between cumulative CO_2 emissions and peak global mean temperature is well established in the literature and robust for cumulative total CO_2 emissions up to about 2000 PgC. It is consistent with the relationship inferred from past cumulative CO_2 emissions and observed warming, is supported by process understanding of the carbon cycle and global energy balance, and emerges as a robust result from the entire hierarchy of models.

In the context of the near proportional relationship between $CE(t)$ and $\Delta T(t)$, the anthropogenic impact on the global temperature increase can be approximated in continuous time by

$$T(t)-T(0)=\Lambda\int_{s=0}^{t}E(s)ds, \tag{2.3}$$

where $CE(t)=\int_{s=0}^{t}E(s)ds$ denotes cumulative global carbon emissions up to time t and Λ is the TCRE. Taking the time derivative of (2.3), we obtain

$$\dot{T}(t)=\Lambda E(t),\ \Lambda=1.7\pm0.4 \text{ °C per TtC.}$$

This linear relationship provides a simplification of climate models and the current research on the economics of climate change has started using it.

Following this presentation of the basic mechanism driving the global mean temperature and the basic links with the economy, we proceed in the next chapter to present the coupled economy–climate models which are used for policy design, and to describe in broad terms a first approach to the study of monetary policy under conditions of climate change.

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3 Coupling the Economy and Climate

3.1 Modeling the economy

3.1.1 Real business cycle theory

In recent years, an increasing number of monetary and fiscal authorities all around the world have adopted the methodologies developed by the modern dynamic macroeconomics literature. Modern macroeconomic theory starts with the view that growth, cycles and policy need to be studied jointly. For this purpose, the same theory uses artificial model economies that, although simple, can mimic important aspects of the behavior of actual economies through time. A distinguishing feature of these model economies is that the main determinant of economic outcomes is agents' dynamic decision problems. In particular, as Lucas (1976) established, to understand growth, cycles and policy, it is necessary to use dynamic model economies consistent with rational behavior on the part of economic players (at least in the medium and long term) and general equilibrium.

Kydland and Prescott (1982) and Long and Plosser (1983) were the first to illustrate the promise of this approach. These models are known as the non-monetary real business cycle (RBC) models and, in contrast to old-style, Keynesian macroeconometric models which relied on ad-hoc behavioral relationships, are based on microfounded, optimizing behavior and a general equilibrium framework. RBC models focused mainly on the impact of technology shocks (see Plosser, 1989, for an overview) and showed that business cycle research is possible without being subject to the Lucas (1976) critique. However, they did not leave much scope for monetary policy analysis.

In particular, RBC modeling rested on the following basic claims (see Gali, 2015):

- First, cyclical fluctuations did not necessarily signal an inefficient allocation of resources, but could instead be interpreted as an equilibrium outcome resulting from the economy's response to exogenous variations in real forces. An important implication of this view is that stabilization policies may be neither necessary nor desirable whereas they can turn out to be counterproductive.

- Second, these models have highlighted the importance of technology shocks as a source of economic fluctuations. This was mainly based on the ability of the baseline RBC model (see below) to generate 'realistic' fluctuations in output and other macroeconomic variables, even when variations in total factor productivity –calibrated to match the properties of the Solow residual– are assumed to be the only exogenous driving force.
- Last but not least, this theory sought to explain economic fluctuations with no reference to monetary factors, and hence no reference to the role of monetary policy.

Therefore, given the above, the emphasis placed on the quantitative aspects of RBC modeling is rather expected. This emphasis is reflected in the central role given to the calibration, simulation and evaluation of RBC models. In particular, this approach means that: first, we set as many parameter values as possible according to the balanced-growth path conditions of the model economy; second, we use this model to generate simulated time series; third, we confront these generated time series with analogous statistics from the actual economy under study; and finally, we use the simulated model to conduct various (policy) experiments.

The baseline RBC model

The flagship and, at the same time, the simplest version of these models is the optimal neoclassical stochastic growth model, widely known as the baseline RBC model. In this setup, a single consumer-producer chooses a utility maximizing consumption profile subject to the income constraint she or he faces. In particular, the consumer-producer aims at maximizing her/his intertemporal welfare given by:

$$E_t \sum_{t=0}^{\infty} \beta^t u\left(c_t\right) \equiv E_t \sum_{t=0}^{\infty} \beta^t \log\left(c_t\right),$$

subject to the budget constraint:

$$c_t + k_{t+1} - \left(1-\delta\right)k_t = A_t k_t^{\alpha}. \tag{3.1}$$

For simplicity, the labor supply is assumed to be inelastic and fixed at unity, and hence the consumer-producer derives utility only from private consumption. Again for simplicity, the utility function can be assumed to be logarithmic. The constraint faced by the agent in equation (3.1) states that all output produced can be consumed and/or invested in new physical capital. The production function is the standard neoclassical production function, which exhibits constant returns to scale. The above maximization problem yields the following pair of dynamic equations:

$$E_t c_{t+1} = \beta E_t c_t \left(1-\delta+\alpha A_t k_t^{\alpha-1}\right),$$

$$c_t + k_{t+1} - \left(1-\delta\right) k_t = A_t k_t^{\alpha},$$

where A_t follows

$$A_t = A_0 e^{z_t}, \tag{3.2}$$

and where A_0 is given, say it is the long-run value of A_t. Equation (3.2) indicates that A_t fluctuates around its long-run value. Moreover, it implies that $\log\left(A_t\right) = \log\left(A_0\right) + z_t$. In other words, $\log\left(A_t\right)$ has a constant term, $\log\left(A_0\right)$, and a cyclical component, z_t. Regarding the structure of the cyclical component, z_t, it is usually assumed that $z_t = \rho z_{t-1} + \varepsilon_t$. This stochastic process is called AR(1), i.e., a first-order autoregressive process. It is autoregressive because it looks like a regression of z_t on itself, with one lag. The usual assumption here is that ε_t is independently and identically distributed and follows the normal distribution with $E_t \varepsilon_t = 0$, whereas it has constant variance, σ_ε^2. Hence, in this setup, the stochastic productivity is the only source of uncertainty in the economy and is the engine of the RBC methodology.

3.1.2 Dynamic stochastic general equilibrium models

Nowadays, the methods of the so-called RBC approach are widely used in work on fiscal and public finance policy, monetary economics, international economics, labor economics, asset pricing, political economy and so forth. In contrast to early RBC studies, recent macroeconomic models include, among others, market imperfections, policy failures and several shocks. These models, known as **dynamic stochastic general equilibrium** or **DSGE** models, are established as the laboratory in which modern macroeconomic theory and policy are conducted (for reviews, see e.g. Cooley and Prescott, 1995, King and Rebelo, 1999, Rebelo, 2005, Kydland, 2006, McGrattan, 2006).

In particular, these models combine, at the same time, three distinct features: a dynamic nature, a general equilibrium framework, and the existence of various (technological or policy) shocks. Their dynamic character follows from the fact that agents' expectations about future uncertain outcomes play an important role in determining the current macroeconomic outcomes. Moreover, their general equilibrium structure captures the interlinkages between economic policy and agents' actions. Finally, the existence of shocks, which trigger economic fluctuations, allow for a more sophisticated study of both the transmission of shocks to the economy and how the economy returns to normal economic activity after the absorption of the shock.

In other words, due to the above-mentioned characteristics, a DSGE model is theoretically able to account for interconnections between different sectors of the economy and can identify sources of fluctuations, answer questions about structural changes, assess the impact of policy changes, perform counterfactual scenarios and so on. Due to these facts, DSGE models have caught the attention of central banks (and also fiscal authorities). In general, the benchmark DSGE model is used to assess the impact of a variety of shocks, such as those arising from behavioral changes concerning households' and firms' decisions, increases in government spending, increases in the currency risk premium and tightening of monetary policy.

Most DSGE models designed for policy use are characterized by a fairly standard structure. In particular, they 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. As already noted, the equations describing these blocks have been derived from microfoundations which in turn are based on specific assumptions regarding the behavior of the main economic players in the economy, such as households, producers, banks and monetary and fiscal authorities. These agents interact through markets that may or may not clear every period, and this is the process that leads to the general equilibrium nature of these models. In other words, DSGE models result from the understanding that policy analysis can be satisfactorily carried out only when the optimizing behavior of agents at the microeconomic level is well understood and taken into account.

Moreover, over the past 20 years there has been remarkable progress in the specification and estimation of DSGE models (see e.g. Fernández-Villaverde, 2010, Fernández-Villaverde et al., 2015). In particular, most DSGE models available in the literature have combined the real business structure discussed above with elements of the new-Keynesian paradigm.[2] These advanced models are usually (open or closed economy) fully microfounded models with real and nominal rigidities (see, for instance, Smets and Wouters, 2007, Christiano et al., 2005). In these models, households consume, decide how much to invest and are monopolistic suppliers of

2 As highlighted by Gali and Gertler (2007), the new Keynesian paradigm that emerged in the 1980s was an attempt to provide microfoundations for Keynesian concepts such as inefficiency of aggregate fluctuations, nominal price stickiness and the non-neutrality of money. In contrast, the RBC literature aimed to build quantitative macroeconomic models from explicit optimizing behavior at the individual level (see Mankiw, 2006).

differentiated types of labor, which allows them to set wages. In turn, firms hire labor, rent capital and are monopolistic suppliers of differentiated goods, which allows them to set prices. Both households and firms face a large number of nominal frictions (e.g., sticky wages and prices or partial indexation of wages and prices) which limit, in each respective case, their ability to reset wages or prices. On the real side, capital is accumulated in an endogenous manner and there are real rigidities arising from adjustment costs to investment, variable capital utilization or fixed costs. Households' preferences display habit persistence in consumption, and the utility function is separable in terms of consumption, leisure and real money balances.

With respect to policy, fiscal policy is usually restricted to a Ricardian setting (for exceptions, see e.g. Forni et al., 2009), while monetary policy is conducted through an interest rate feedback rule,[3] in which the policy nominal interest rate is set in response to deviations from an inflation target and some measure of economic activity (e.g., the output gap). Furthermore, some degree of interest rate smoothing is often assumed.

As already mentioned, the above setup is enriched with a stochastic structure associated with a variety of different types of shocks, such as supply side shocks (productivity and labor supply), demand side shocks (preference, investment specific, government spending), costpush or markup shocks (price markup, wage markup, risk premium) and monetary shocks (interest rate or other target variables). These shocks are often assumed to follow a first-order autoregressive process, such as the one shown in equation (3.2). In general, the framework is designed to capture plausible business cycle dynamics of an economy. On the monetary side, it attempts to capture some of the most important elements of the transmission mechanism.

This model approach, which reflects the advances made in DSGE modeling over the past two decades, faces some important challenges (see e.g. Blanchard, 2016). In particular, it could be said that more work is required in: modeling financial markets (see e.g. Viziniuc, 2015); incorporating more explicitly the role of fiscal policies; improving the interaction between trade and financial openness; modeling labor markets; and modeling inflation dynamics (for instance, regarding the role of expectations and pricing behavior). Of course, additional aspects have to be considered when modeling small open economies, or a monetary union.

3 For a review of DSGE models and monetary policy, see e.g. Christiano et al. (2011).

3.1.3 Solution methodology

The 'recipe' for building a DSGE model, solving it and comparing it to actual data includes several steps which can be summarized as follows (see e.g. Flotho, 2009):

- First, we have to set up the economic model.
- Second, we need to derive the first-order equilibrium conditions which, together with the structural equations, build a system of nonlinear stochastic difference equations.
- Third, as this system usually does not have a closed-form analytical solution, we need to approximate the solution in the neighborhood of a given point, in most cases the non-stochastic steady state. So in this step, we determine the non-stochastic long-run equilibrium of the model economy.
- Fourth, we either (log-)linear approximate the system of nonlinear stochastic difference equations around the steady state leading to a system of linear difference equations in state-space form and we solve this system with the help of the usual procedures, or we take a second- (or higher-) order approximation of the same set of equations around the steady state.
- Fifth, we calibrate the parameters of the model, or estimate them, or both (see e.g. Fernández-Villaverde, 2010, Fernández-Villaverde et al., 2015).
- Sixth, we calculate the variances and conduct a variance decomposition of the underlying shocks and impulse response functions of the variables of interest.
- Finally, we evaluate the model by looking at measures of fit to the data.

Note that the above-described procedure is commonly applied when analyzing infinite horizon DSGE models with representative agents.

3.2 Integrated assessment models: the economy under climate change

Many modeling frameworks have been developed to provide an understanding of the drivers of climate change and to assist policy formation. As Nikas et al. (2018) point out, when climate change emerged as a serious issue in the 1970s, there were no theoretical tools that could provide a more integrated understanding of the phenomenon or provide richer insights into policy response. Models of physical dimensions of the climate system (mostly ecosystem models) were extended to consider the processes by which GHG emissions were generated and could be limited. General circulation models that dealt with atmospheric parts of the climate system were linked to ocean models. Economists modified global energy–economy analysis to project GHG emissions, consider ways to reduce them, and incorporate aggregated physical dimensions of the climate system. Scientists from different disciplines linked models and analysis to provide a more integrated understanding of different, interrelated facets of a highly complex phenomenon (see e.g. Weyant, 2009).

At a broad level we can see the following interlinked chain of interactions. Human-induced climate change results from an increase in emissions of GHGs and their levels of concentration in the atmosphere. Climate science tells us how different concentration levels of GHGs may affect the temperature, precipitation, cloud formation, wind and sea level rise. These changes in turn result in various physical, environmental and social impacts such as changes in crop yields, water supply, species loss and migration. These impacts can then be translated into monetary terms, or processed through a model of the economy, to give a single measure of the economic cost of climate change. As these changes take place over time, models attempt to project parts or the whole dynamic process of increasing emissions, temperature changes, physical impacts and economic damages. The economy is not only affected by climate change, but it is also the perpetrator of climate change as growth in production and consumption gives rise to more GHG emissions. The most important part of the economy – which determines the rate of emissions – is the energy system or the forms and uses of energy. Each part of this climate–economy interaction is characterized by uncertainty and some degree of scientific disagreement (see e.g. Weitzman, 2010).

Various ways of climate–economy modeling can, to a large extent, be understood by the different ways in which they model parts of this highly interconnected process. Figure 3.1 provides a depiction of climate–economy dynamics, identifying four key modules of climate–economy modeling. The climate module describes the link between GHG emissions, atmospheric concentrations and the resulting variation in temperature and other climatic changes (e.g., precipitation, cloud cover, extreme weather events, climate discontinuities). The impacts module (or damage function) expresses physical or environmental outcomes as a function of climate variables. For instance, a model might have an agricultural damage function relating variability in temperature, precipitation and cloud cover to crop yields. An economy module might describe the dynamics or growth of an economy, how emissions vary with growth and climate policies, and how climate-induced physical and environmental changes could 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.

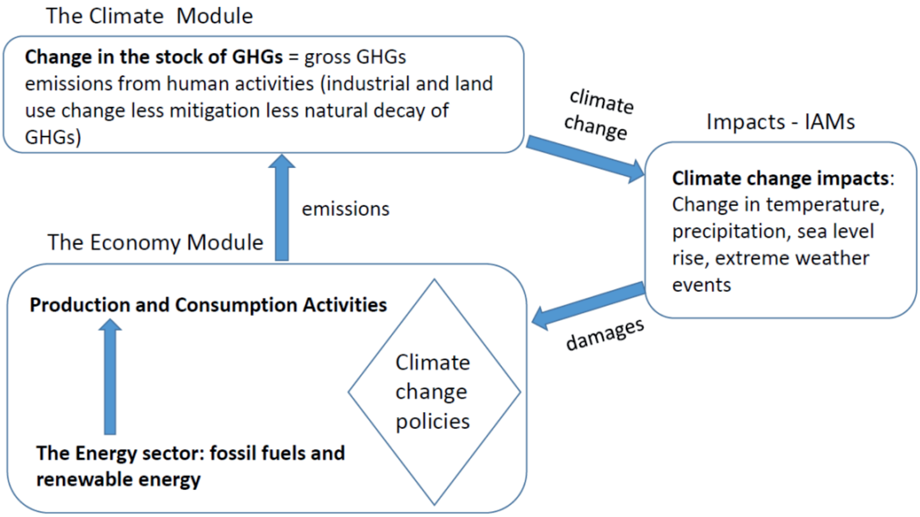

Figure 3.1 Climate–economy dynamics

As a result of the above-described attempt to link climate with the economy – and moreover in order to be able to assess the role of economic policy in dealing with climate change – global economy–climate models, known as integrated assessment models (IAMs), have been constructed.

3.2.1 Classifying climate–economy models

The great variety of climate–economy models reflect in part the range of underlying scientific disciplines influencing their development, alternative methodologies and assumptions, as well as the different questions or issues they address. The large and growing number of models and their relative complexity can make it bewildering to distinguish between them or understand their unique attributes. There are already many good reviews of different categories of integrated assessment or climate–economy models in the literature (see e.g. Hope and Helm, 2005, Füssel, 2009). Drawing on the various classifications[4] in the literature, we can distinguish between

4 See especially Füssel (2010), Ortiz and Markandya (2010), Stanton et al. (2009), and Soderholm

six general model structures or approaches (see e.g. Nikas et al., 2018). These are distinguished primarily by how the economy is modeled and the way in which the other three modules (climate, impacts, energy) are integrated.

(1) Optimal growth IAMs represent the economy as a single, all-encompassing sector. They are designed to determine the climate policy that maximizes welfare over time. They tend to be fairly simple, highly aggregated and transparent models that capture the trajectory of an economy and its interaction with climate in a fully integrated fashion, i.e., all modules are represented and endogenously determined.

(2) Computable general equilibrium (CGE) models have a more detailed representation of the economy with multiple sectors and often include higher resolution of energy technologies and regional detail. Rather than seeking optimal policies, they consider the impacts of specific policies on economic, social and environmental parameters. The richer representation of the economy comes at a cost, in that the growth of the economy is harder to model. Notice here that the neoclassical growth model can also be viewed as a CGE model with just one sector.

(3) Partial equilibrium non-energy sector models provide a detailed analysis of the interaction between environmental impacts and a particular sector of the economy. These are usually used to assess potential climate-induced damages to a sector of the economy and are often linked to CGE models.

(4) Energy systems models are partial equilibrium models that provide a detailed account of energy technologies and their associated costs. These are used, inter alia, to determine the least cost ways of attaining GHG emissions reductions, or the costs of alternative climate policies. They are often linked with CGE or macroeconometric models.

(5) Macroeconometric models such as CGE models can be quite detailed in terms of energy technologies and geographic scope and are also used to evaluate alternative climate policies, but they differ in that they do not assume that consumers and producers behave optimally or that markets clear. Instead they use econometrically-estimated parameters and relations to dynamically simulate the behavior of the economy.

(2007), although their classifications do not fully align with each other or with the one presented here. Füssel, following an older tradition, divides them according to the kind of decision-analytical frameworks to which they are applied. Ortiz and Markandya classify IAMs by whether all four modules (climate, impacts, economy, energy) are used and how they are combined. Stanton et al. divide them according to model structures.

(6) Other IAMs refers to models that may have little in common except that they do not fit neatly into any of the previous, well-known groups. A key departure is that they model the economy in a highly 'reduced form', or simply use exogenous growth scenarios (no model at all). The PAGE2002 model, known for being the model used by the Stern (2007) review, belongs to this class of models.

We will focus on models that follow approaches (1) and (2). As Nordhaus – who has done pioneering work on integrated assessment modeling – points out, "Integrated assessment models (IAMs) can be defined as approaches that integrate knowledge from two or more domains into a single framework" (Nordhaus, 2013, pp. 1069-1070). Indeed, IAMs have proved to be crucially important tools to analyze the dynamic interactions between the economic, energy and climate systems. Over the past two decades, since the first models attempting to link climate with the economic system appeared (see Nordhaus, 1994, Nordhaus and Yang, 1996), research using IAMs has made large steps forward and there is now a wide variety of different models routinely used to assess climate policies, as demonstrated by the increasing number of comparative exercises (see e.g. Clarke et al., 2009, Calvin et al., 2011, Luderer et al., 2012).

In other words, the task of IAMs is to pull together the different aspects of a problem so that projections, analyses and decisions can simultaneously consider all important endogenous variables. IAMs generally do not pretend to have the most detailed and complete representation of each included system. Rather, they aspire to have, at a first level of approximation, models that operate all the modules simultaneously and with reasonable accuracy.

A brief description of representative integrated assessment models

Gillingham et al. (2015) analyzed ways in which to model parametric uncertainty in climate change, using six representative IAMS which have been used in IPCC assessment reports, and SCC estimation for policy purposes. Uncertainty will be discussed in Chapter 7 (Section 7.7), but below we provide a brief description of the main characteristics of these six models, which are the DICE model, the FUND model, the GCAM model, the MERGE model, the MIT IGSM model and the WITCH model.

The DICE (Dynamic Integrated model of Climate and the Economy) was first developed around 1990 and has gone through several extensions and revisions, with the latest published version being DICE2016R.[5] A detailed description of DICE can

5 More information is available at https://sites.google.com/site/williamdnordhaus/dice-rice.

be found in Nordhaus and Sztorc (2013). The DICE model is a globally aggregated model of neoclassical growth theory, which contains a climate module in addition to the economy module. The two modules interact. In DICE, the aggregate economy accumulates capital and generates industrial emissions. Emissions increase the stock of GHGs, which in turn increases the global mean temperature. Temperature increase generates damages which reduce aggregate output. Industrial emissions can be reduced through costly mitigation. DICE includes all major elements of the economic and the climate system in a highly aggregated fashion. The model contains about 25 dynamic equations and identities, including those for global output, CO_2 emissions and concentrations, global mean temperature and damages and can be run in either an Excel version or in the preferred GAMS version. In the Gillingham et al. (2015) study, the December 2013 version was used, which adds loops to calculate the outcomes for different uncertain parameters.

The FUND model (Climate Framework for Uncertainty, Negotiation, and Distribution) was developed to assess the impacts of climate policies in an integrated framework. FUND uses as input exogenous scenarios of major economic variables and then perturbs them to produce the impacts of climate change. It is a regional multi-GHGs model which contains 16 regions and five GHGs. Climate change impacts on agriculture, forestry, sea-level rise, health, energy consumption, water resources, unmanaged ecosystems and storms are calculated in money terms. The impacts in each sector are calculated by using different impact functions. The model runs from 1950 to 3000 in time steps of one year. The source code, data and a technical description of the model are public (available at http://www.fund-model.org), and the model has been used by other modeling teams (e.g. Revesz et al., 2014). FUND was originally created by Richard Tol (1997) and is now jointly developed by David Anthoff and Richard Tol.

The GCAM (Global Change Assessment Model) is a global integrated assessment model of energy, economy, land-use and climate. GCAM is based on the Edmonds and Reilly (1983a, 1983b, 1983c) model, which integrates an economic module that includes the global economy, energy systems, agriculture and land use, with a geophysical module including terrestrial and ocean carbon cycles, and a suite of coupled gas-cycle and climate models. The climate and physical atmosphere in GCAM is based on the Model for the Assessment of Greenhouse-Gas Induced Climate Change (MAGICC) (Meinshausen et al., 2011). The economic module of GCAM includes 14 geopolitical regions which interact through international trade in energy commodities, agricultural and forest products, and emission permits. The model is dynamic and is solved recursively. Full documentation is available at a GCAM wiki (Calvin et al., 2011). GCAM is open-source, but is primarily developed and maintained by the Joint Global Change Research Institute.

The MERGE (Model for Evaluating Regional and Global Effects of greenhouse gas reduction policies) model is a regional IAM which was introduced by Manne et al. (1995) and has been continually developed. MERGE is formulated as a multi-region dynamic general equilibrium model with sub-models for the energy system and the climate. The economy is represented by a Ramsey growth model in which the production function is represented by a nonlinear nested form in which inputs are capital, labor, electric and non-electric energy, and aggregate output is allocated among consumption, investment and energy costs. Recent versions of MERGE associate Negishi weights with each region. The climate model contains carbon dioxide, methane and nitrous oxide. Temperature evolves as a two-box lag process, where uncertainty about climate sensitivity is considered jointly with uncertainty about the response time of actual temperature and aerosol forcing. The version used for the Gillingham et al. (2015) study includes 10 model regions and runs through the year 2100, with climate variables projected for another 100 years.

The MIT IGSM (Integrated Global Systems Model) was developed in the early 1990s and has been updated in Sokolov et al. (2009) and Webster et al. (2012). The version of the economic component used by Gillingham et al. (2015) is the version described in Chen et al. (2015). The model contains the following components: an economic model of human activities and emissions (the Emissions Prediction and Policy Analysis Model); an atmospheric dynamics, physics and chemistry model, with carbon cycle and sea ice sub-models; a land system model which describes the global, terrestrial water and energy budgets, and terrestrial ecosystem processes. The atmospheric model is based on the Goddard Institute for Space Studies general circulation model, which includes all significant greenhouse gases and 11 types of aerosols. The general circulation model contains the atmosphere and its interactions with oceans, terrestrial vegetation and the land surface. Its economic component represents the economy and anthropogenic emissions. The economic component is a general equilibrium model of the world economy.

The WITCH (World Induced Technical Change Hybrid) model was developed in 2006 (Bosetti et al., 2006) and has been further developed and extended since then. WITCH is a multi-regional model which divides the world into 13 major regions. The economy module in each region is described by a Ramsey-type neoclassical optimal growth model, in which forward-looking central planners maximize the present discounted value of utility of each region. The distinguishing features of WITCH are the incorporation of endogenous technical change and the game-theoretic approach. The regions of the model interact strategically, while technical change is induced by innovation and diffusion. Non- CO_2 GHGs are included in the updates of the model, along with abatement options and emission reduction from deforestation and degradation. GHG emissions and concentrations are used as inputs in a climate model to generate radiative forcing and global mean temperature paths. The version used by Gillingham et al. (2015) runs for 30 five-year periods and contains 35 state variables for each of the 13 regions, running on the GAMS platform.

3.2.2 Modern environmental macroeconomic models

In this section, we present the main features of modern environmental macro-economic modeling, and briefly discuss the approaches suggested by Nordhaus (2014) and Golosov et al. (2014).

Hassler et al. (2016) discuss climate change and resource scarcity from the perspective of modern macroeconomic modeling and quantitative evaluation. Their focus is on building toward a microeconomics-based IAM. The authors point out that most IAMs are not microeconomics-based macroeconomic models, although they recognize that Nordhaus's work is a notable exception. On the other hand, they argue that the models developed by Nordhaus, i.e., the DICE and RICE models, are closer to what most people consider to be pure planning problems. This implies that they do not present a complete market structure, and hence a detailed analysis of policies – such as a carbon tax or a quota system – is not feasible. Hassler et al. thus raise the issue that since most of the models in the literature are simply planning problems, there is an important question that cannot be addressed in the known contexts: What happens if authorities pursue a suboptimal policy? They assert that the relevant research should put more focus on the approach used in modern macroeconomics.

Specifically, Hassler et al. describe a general framework which could then be modified properly in order to be able to address issues such as those mentioned in the previous paragraph. In particular, they consider a growth economy inhabited by a representative agent, whose intertemporal utility is given by:

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

with a resource constraint of the form

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

in which S obeys the law of motion:

$$S_{t+1} = H(S_t, E_t).$$

Relative to the standard macroeconomic setting, the new variables are S and E. In particular, S is a stock variable which affects utility directly and/or affects production, whereas E is a flow variable which represents an activity that influences the stock. For instance, S could be identified as clean air or biodiversity, and E could be identified as an activity that, on the one hand raises output, but on the other hand lowers the stock S. Since the aim of the authors is to construct a model that connects climate and the economy, they suggest that S_t could be thought of as the climate at time t or a key variable that influences it, namely, the stock of carbon in the atmosphere; and E_t could be emissions of CO_2 caused by the use of fossil fuel in production. Then, the carbon stock S hurts both utility and output. In order for this setup to be fully adequate to examine the climate issue, another stock – that of the available amounts of fossil fuel, which are depletable resources in finite supply – should be present. Also, technological issues should be taken into account, since it is possible for technology to enhance production possibilities in a neutral manner, but also to amount to specific forms of innovation aimed at developing non-fossil energy sources or, more generally, saving on fossil-based energy.

In this setup, Hassler et al. (2016) find it reasonable to assume that the evolution of S is simply a byproduct of economic activity or, in other words, an externality. Thus, comparing the optimal path of K and S to the market outcome can be important, in the sense that it might reveal the type of policies needed to move the *laissez-faire* outcome toward the optimum.

Then, as the authors suggest, the modern macroeconomic approach would be to: (i) define a dynamic competitive equilibrium including environmental policy (say a unit tax on E), with firm, consumers and markets clearly spelled out, (ii) then look for insights about optimal policy, both qualitatively and quantitatively (based on, say, calibration), and (iii) perhaps characterize outcomes for the future for different (optimal and suboptimal) policy scenarios.

3.2.3 The DICE-2013R model

The framework mainly used by Nordhaus in his relevant studies (see e.g. Nordhaus, 1977, Nordhaus and Boyer, 2000) is a microeconomics-based computational macroeconomic model called the Regional Dynamic Integrated model of Climate and the Economy (RICE) or, in its earlier one-region version, Dynamic Integrated model of Climate and the Economy (DICE), which combines an economic sector with a climate system. In other words, the DICE model depicts a one-region world and the RICE model a multi-region world. In what follows, and since RICE is a multi-region version of the DICE model, we will discuss the main features of the latter.

The DICE model views climate change in the framework of economic growth theory. In the standard neoclassical optimal growth model (Ramsey model), society invests in capital goods, exchanging, in this way, current consumption for consumption in the future (see e.g. Ramsey, 1928, Koopmans, 1967). The DICE model modifies the Ramsey model to include climate investments, which are analogous to capital investments in the standard model. The model contains all elements from economics through climate change to damages. The geophysical equations are simplified versions derived from large models or model experiments.

Thus the model optimizes a social welfare function, which is the discounted sum of the population-weighted utility of per capita consumption. Net output is a function of gross output, in the sense that net output is gross output reduced by damages and mitigation costs. In the specification used, net output is output net of damages and abatement. For gross output, it is assumed that it is a Cobb-Douglas function of capital, labor and technology. Labor is proportional to population, while capital accumulates according to an optimized savings rate. The additional variables in the production function are the damage function (reflecting the climate change) and the abatement-cost function.

Here it should be noted that a new and important concept that has taken center stage in economic and policy discussions about global warming is the **social cost of carbon**, or **SCC**. This term reflects the economic cost caused by an additional ton of CO_2 emissions or its equivalent. More precisely, it is the change in the discounted value of the utility of consumption per unit of additional emissions, denominated in terms of current consumption. From another – more mathematical – perspective, the SCC is the shadow price of carbon emissions along a reference path of output, emissions and climate change. Hence the economic impacts or damages of climate change are a key component in calculating the SCC. The DICE model takes globally-averaged temperature change as a sufficient statistic for damages. In particular, it assumes that damages can be approximated reasonably well by a quadratic function of temperature change.

Therefore, the aim of the DICE model is to estimate the SCC under differing assumptions regarding policy, damages and discounting. Why is this important? It is important because it allows us to understand and design the implementation of specific climate policies. The model can also be used as a complete setting for predicting the climate in the future – along with the paths for consumption, output and so forth – for different policy paths. It may also provide us some insight into questions such as: How sharply should countries reduce CO_2 emissions? What should the time profile of emissions reductions be? How should the reductions be distributed across industries and countries?

There are also important issues regarding the instruments that should be used to impose cuts on consumers and businesses. Should there be a system of emissions limits imposed on firms, industries and nations? Or should emissions reductions be primarily induced through green taxes? Should green industries be subsidized? What should the relative contributions of rich and poor households or nations be? Are regulations an effective substitute for fiscal instruments?

Equations of the DICE model

Following Nordhaus (2014), we now present the main algebraic characteristics of the DICE model. In particular, as already mentioned, the DICE model optimizes a social welfare function, W, which is the discounted sum of the population-weighted utility of per capita consumption. In equation (3.3), $c(t)$ is per capita consumption, $L(t)$ is population, and $R(t) = (1+\rho)^{-t}$ is the discount factor on utility or welfare, where ρ is the pure rate of social time preference or generational discount rate, so:

$$\sum_{t=1}^{T\max} U[c(t), L(t)]R(t). \tag{3.3}$$

The utility function is assumed to be of constant elasticity with respect to consumption of the form $U(c) = c^{1-\alpha}/(1-\alpha)$. The parameter α can be thought of as generational inequality aversion in this context. Net output, $Q(t)$, is a function of gross output, $Y(t)$. Net output is gross output reduced by damages and mitigation costs,

$$Q(t) = \Omega(t)[1-\Lambda(t)]Y(t) = C(t) + I(t), \tag{3.4}$$

where $Q(t)$ is output net of damages and abatement, and $Y(t)$ is gross output. Gross output is produced by capital, labor and technology through a Cobb-Douglas production function. Also, $C(t)$ is consumption and $I(t)$ is gross investment. Labor is proportional to population, while capital accumulates according to an optimized savings rate. The additional variables in equation (3.4) are $\Omega(t)$ and $\Lambda(t)$, which represent the damage function and the abatement-cost function, respectively. The damage function is defined as $\Omega(t) = D(t)/(1+D(t))$, where:

$$D(t) = \psi_1 T_{AT}(t) + \psi_2 (T_{AT}(t))^2. \tag{3.5}$$

Equation (3.5) describes the economic impacts or damages of climate change, which is a key component in calculating the SCC. The DICE-2013R model takes globally-averaged temperature change (T_{AT}) as a sufficient statistic for damages. In other words, this equation assumes that damages can be approximated reasonably well by a quadratic function of temperature change.[6]

Uncontrolled industrial CO_2 emissions are given by a level of carbon intensity, $\sigma(t)$, times gross output. Total CO_2 emissions, $E(t)$, are equal to uncontrolled emissions reduced by the emissions-reduction rate, $\mu(t)$, plus exogenous land use emissions, so:

$$E(t) = \sigma(t)(1-\mu(t))Y(t) + E_{Land}(t). \tag{3.6}$$

The geophysical equations link GHG emissions to the carbon cycle, radiative forcings and climate change. The equations of the carbon cycle for three reservoirs are represented by:

$$M_j(t) = \phi_{0j} E(t) + \sum_{i=1}^{3} \phi_{ij} M_i(t-1). \tag{3.7}$$

The three reservoirs are $j =$ AT, UP, and LO, which are the atmosphere, the upper oceans and biosphere, and the lower oceans, respectively. The parameters i, j represent the flow parameters between reservoirs per period. All emissions flow into the atmosphere. As with many other components of the DICE model, the simplified carbon cycle is a compromise between scientific accuracy and transparency.

The relationship between GHG accumulations and increased radiative forcing is shown by:

$$F(t) = \eta\{\log_2[M_{AT}(t)/M_{AT}(1750)]\} + F_{EX}(t), \tag{3.8}$$

where $F(t)$ is the change in total radiative forcings of GHGs from anthropogenic

6 We should note that one prime source of structural uncertainty in the economic component of climate change concerns the appropriate way to represent damages from global warming (see Weitzman, 2010). The damage function is a weak link in the economics of climate change, because it is difficult to be specified a priori and because the results from cost-benefit analysis or an IAM can be very sensitive to its functional form – particularly for high temperatures. Ideally, we want an analytically tractable form that adequately captures the economic reality of global warming. The existing literature offers sparse theoretical guidance and little empirical evidence on why one form of a damages specification should be favored over another.

sources such as CO_2; $F_{EX}(t)$ is exogenous forcings; and the first term is the forcings due to atmospheric concentrations of CO_2.

Forcings lead to warming according to a simplified two-level global climate model:

$$T_{AT}(t) = T_{AT}(t-1) + \xi_1\{F(t) - \xi_2 T_{AT}(t-1) - \xi_3[T_{AT}(t-1) - T_{LO}(t-1)]\} \tag{3.9}$$

$$T_{LO}(t) = T_{LO}(t-1) + \xi_4[T_{AT}(t-1) - T_{LO}(t-1)]. \tag{3.10}$$

In equations (3.9) and (3.10), $T_{AT}(t)$ is the global mean surface temperature and $T_{LO}(t)$ is the mean temperature of the lower oceans.

Using equations (3.3)–(3.10), the social welfare function, W, can be maximized in terms of the various exogenous and policy variables. Then the SCC at time t can be defined as:

$$SCC(t) \equiv -\frac{\partial W}{\partial E(t)} / \frac{\partial W}{\partial C(t)}. \tag{3.11}$$

The numerator is the marginal impact of emissions at time t on welfare, while the denominator is the marginal welfare value of a unit of aggregate consumption in period t. The ratio calculates the economic impact of a unit of emissions in terms of t-period consumption as a numeraire. In actual calculations, a discrete approximation of equation (3.11) is taken. Also, note that the SCC is time-indexed, which implies that the marginal cost of emissions at time t (in terms of consumption at time t as a numeraire) changes over time.

Nordhaus estimates the SCC in the DICE model for several alternative scenarios which reflect differing assumptions about policy, damages and discounting. The most important results derived from Nordhaus's analysis are the following. First, the estimated SCC for 2015 is \$18.60 per ton of CO_2 in 2005 US international prices. Second, the DICE model results are lower than in some models in the relevant literature (i.e., the Policy Analysis of the Greenhouse Effect (PAGE) model)[7] but higher than others (i.e., the FUND model). Third, the major open issue concerning

7 The PAGE model projects future increases in global mean temperature, the economic costs of damages caused by climate change, and the economic costs of mitigation policies. It has a relatively simple economic structure, taking output and emissions as exogenous with many periods, countries and sectors. The major innovations are detailed inventories of GHGs; reduced-form treatment of the atmospheric chemistry of gases; simplified global and regional climate models, including of aerosols; and detailed regional impacts. Moreover, the PAGE model makes uncertainty a central focus, with 31 uncertain variables (such as climate sensitivity, carbon cycle dynamics, impacts and discontinuous impacts). The damage structure is highly developed, with catastrophic thresholds and sharp discontinuities introduced probabilistically. The model is proprietary but is available to others with permission and credits.

the SCC continues to be the appropriate discount rate. Fourth, the use of the SCC in regulatory policies in the energy sector is increasingly important, but analyses of its application have not sufficiently considered issues such as leakage, distortionary taxes and the question of whether to use global or domestic SCCs.

3.2.4 Intertemporal environmental macroeconomic models

In line with the approach used by Nordhaus, Golosov et al. (2014) use a quite similar model to study the interconnection between climate and the economy, although there are some differences regarding some features of the climate system they choose to incorporate into their IAM. Regarding the economic part, Golosov et al. use an extension of a non-renewable resource model along the lines of Dasgupta and Heal (1974), in order to incorporate a climate externality. In particular, Golosov et al. analyze a dynamic stochastic general equilibrium (DSGE) model with an externality – through climate change – from using fossil energy.

Golosov et al. consider a version of the multi-sector neoclassical growth model with $I+1$ sectors. Time is discrete and infinite. There is a representative household which derives utility from private consumption as:

$$E_0 \sum_{t=0}^{\infty} \beta^t U(C_t),$$

where U is a standard concave period utility function, C is consumption, and $\beta \in (0,1)$ is the discount factor.

The production side of the economy consists of what the authors label as a final-goods sector, which is denoted by $i=0$ and with output Y_t, and by $i=1,\ldots,I$ intermediate-goods sectors that produce energy inputs E_i, $i=1,\ldots,I$, for use in all sectors. The feasibility constraint in the final-goods sector is:

$$C_t + K_{t+1} = Y_t + (1-\delta)K_t. \tag{3.12}$$

The left-hand side of equation (3.12) reflects resource use, that is, consumption and next period's capital stock. The first term on the right-hand side of equation (3.12), Y_t, is the output of the final good. The second term is undepreciated capital. Output in the final-goods sector is described by an aggregate production function,

$$Y_t = F_{0,t}(K_{0,t}, N_{0,t}, E_{0,t}, S_t).$$

The arguments of $F_{0,t}$ include the standard inputs $K_{0,t}$ and $N_{0,t}$ (capital and labor used in this sector), along with $E_{0,t} = (E_{0,1,t},\ldots, E_{0,I,t})$ denoting a vector of energy inputs used in this final sector at t. The sub-index t on the production function captures the possibility of technical change. This change can appear in a variety of ways, for example, as an overall increase in productivity, a changed transformation technology across basic inputs (such as technical change saving on specific inputs), or a change in the way energy services are produced. This change can be either deterministic or stochastic. Finally, Golosov et al. also allow a climate variable S_t to affect output.

The effect of S_t on aggregate production could, in general, be either positive or negative, and Golosov et al. use the word 'damage' with this understanding. They then focus on various sorts of damages that are all captured through the production function. The link between $F_{0,t}$ and S will be specified below. Note that climate is viewed as being sufficiently well represented by one variable only: S can be considered as the amount of carbon in the atmosphere. The authors defend their assumption by arguing that this is reasonable, given available medium-complexity climate models used in the natural sciences. These models imply that the current climate is described quite well by current carbon concentrations in the atmosphere (e.g., lags due to ocean heating are not so important). The authors also allow damages, or the mapping from the atmospheric carbon concentration, to have a stochastic component. Their assumption that S_t affects production only is made mainly in order to make their analysis closer to, and easier to compare with, Nordhaus's RICE and DICE treatments.

Regarding the production of energy services, which are both inputs and outputs, Golosov et al. assume that each component of $E_{0,t}$, $E_{0,i,t}$ is produced by its own technology $F_{i,t}$, which uses capital, labor and a vector of energy inputs. Moreover, some energy sources i are in finite supply, such as oil. For any such energy source *i*, let $R_{i,t}$ denote its beginning-of-period stock at *t*, and let $E_{i,t}$ be the total amount extracted (produced) at time *t*. Then the decumulation equation, or the law of motion, for any exhaustible stock i is:

$$R_{i,t+1} = R_{i,t} - E_{i,t} \geq 0.$$

The production technology for energy from source i, exhaustible or not, is:

$$E_{i,t} = F_{i,t}(K_{i,t}, N_{i,t}, E_{i,t}, R_{i,t}) \geq 0. \tag{3.13}$$

Golosov et al. assume that sectors $i = 1, ..., I_g - 1$ are 'dirty', in the sense of emitting fossil carbon into the atmosphere. Sectors $I_g, ..., I$ are 'clean' or 'green' energy sources, which are not associated with climate externalities. They normalize E_i for $i = 1, ..., I_g - 1$ to be in the same units – that is, one unit of E_i produces one unit of carbon content – and the relative energy efficiencies of different sources of energy are captured implicitly in the production functions.

Turning to the evolution of the climate, the authors assume a general formulation. In particular, they let S_t be a function that maps a history of anthropogenic emissions into the current level of atmospheric carbon concentration, S_t. The history is defined as starting at the time of industrialization, a date defined as $-T$:

$$S_t = S_t\left(\sum_{i=1}^{I_g-1} E_{i,-T}, E_{-T+1}^f, \ldots E_t^f\right), \tag{3.14}$$

where $E_s^f \equiv \sum_{i=1}^{I_g-1} E_{i,s}$ is fossil emissions at *s*. Recall that $E_{i,s}$ is measured in carbon emission units for all i.

Golosov et al. then – by making various simplifying assumptions regarding preferences, damage formulation and the carbon cycle – solve the planning problem, and characterize the solution to it in terms of some key relationships that will subsequently be compared to market outcomes. In particular, the authors follow Nordhaus and assume that damages are multiplicative:

$$F_{0,t}(K_{0,t}, N_{0,t}, E_{0,t}, St) = \left(1 - D_t(S_t)\right) F_{0,t}(K_{0,t}, N_{0,t}, E_{0,t}),$$

where *D* is the damage function. It captures the mapping from the stock of CO_2 in the atmosphere, S_t, to economic damages measured as a percentage of final-good output.

As Golosov et al. discuss, the $D(S)$ mapping can be thought of in two steps. The first is the mapping from carbon concentration to climate (usually represented by global mean temperature). The second is the mapping from the climate to damages. Both of these mappings are associated with significant uncertainty.

For reasons summarized in Roe and Baker (2007) and also explored in Weitzman (2010) and Roe and Bauman (2011), Golosov et al. argue that climatic feedback mechanisms of uncertain strength imply that it is reasonable to think of the warming effect of a given atmospheric CO_2 concentration in terms of a distribution with quite fat tails. Nordhaus explicitly modeled both steps in the mapping from the carbon concentration to damages. Moreover, Golosov et al. show in their numerical section that an exponential specification for $D(S)$ approximates Nordhaus's formulation rather well. Note that here D is allowed to depend on time and, implicitly, on the state of nature in case there is a random element to damages. Then, Golosov et al. parameterize this dependence through the specification

$$F_{0,t}(K_{0,t}, N_{0,t}, E_{0,t}, S_t) = \left(1 - D_t(S_t)\right) F_{0,t}(K_{0,t}, N_{0,t}, E_{0,t}),$$

where $\left(1 - D_t(S_t)\right) = \exp(-\gamma_t(S_t - \overline{S}))$ and where S is the pre-industrial atmospheric

CO_2 concentration.

Finally, regarding the carbon cycle, they assume that:

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

where $d_s \in [0,1]$ for all s. Here, $1 - d_s$ represents the amount of carbon that is left in the atmosphere s periods into the future. Regarding the depreciation structure, Golosov et al. assume that: (i) a share φ_L of carbon emitted into the atmosphere stays in it forever; (ii) a share $1 - \varphi_0$ of the remaining emissions exits the atmosphere immediately (into the biosphere and the surface oceans); and (iii) the remaining share decays at a geometric rate φ. That is:

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

Therefore, the planning problem they solve is:

$$\max_{\{C_t, N_t, K_{t+1}, R_{t,t+1}, E_t, S_t\}_{t=0}^{\infty}} E_0 \sum_{t=0}^{\infty} \beta^t U(C_t), \tag{3.15}$$

subject to equations (3.13), (3.14), (3.15), and the resource constraint of the economy:

$$C_t + K_{t+1} = F_{0,t}(K_{0,t}, N_{0,t}, E_{0,t}, S_t) + (1 - \delta) K_t.$$

Having the solution of the above problem as a benchmark, the authors focus on the decentralized equilibrium (DE) outcome, and characterize the conditions under which it is possible for the DE solution to coincide with the solution to the planning problem. This is in line with the suggestions made by Hassler et al. (2016).

The central result of Golosov et al. (2014) is a simple formula for the marginal externality damage of emissions (or, equivalently, for the optimal carbon tax). This formula, which holds under quite plausible assumptions, reveals that the damage is proportional to current GDP, with the proportion depending on only three factors: (i) discounting, (ii) the expected damage elasticity (i.e., what percent of the output flow is lost from an extra unit of carbon in the atmosphere), and (iii) the structure of carbon depreciation in the atmosphere. Thus the stochastic values of future output, consumption and the atmospheric CO_2 concentration, as well as the paths of technology (whether endogenous or exogenous) and population, and so on, all disappear from the formula.

Golosov et al. (2014) also find, by performing a set of numerical exercises, that the optimal tax should be a bit higher than the median, or most well-known, estimates in the literature. In particular, they evaluate this formula quantitatively and find results that are about twice the size of those put forth by Nordhaus and Boyer (2000). The differences between their findings are due to a variety of differences in assumptions, for example, regarding the carbon depreciation structure. However, it is possible for the specific formula to arrive at estimates that are very close to those generated by Nordhaus, by making appropriate adjustments to carbon depreciation rates, the discount rates, utility-function curvatures and lags in temperature dynamics. Stern (2007) arrived at much higher estimates; if Golosov et al. simply adjust their subjective discount rate down to the level advocated in Stern's report, they obtain an optimal tax rate that is about twice the size of his.

Based on further assumptions about fossil fuel stocks and their extraction technologies and about important sources of output growth, such as total factor productivity (TFP) growth, Golosov et al. (2014) then compute paths for their key variables for a DE economy and compare them to the optimal outcome. In the optimal outcome, coal extraction is much lower than in the DE. The use of oil and green energy is, however, almost identical in the two allocations. The temperature increase will therefore be much smaller if the optimal tax is introduced.

3.2.5 A criticism of integrated assessment models

A criticism of IAMs, and especially the functional forms used for the damage function, is that made by Pindyck (2013, p. 867), who concludes that:

> When assessing climate sensitivity, we at least have scientific results to rely on, and can argue coherently about the probability distribution that is most consistent with those results. When it comes to the damage function, however, we know almost nothing, so developers of IAMs can do little more than make up functional forms and corresponding parameter values. And that is pretty much what they have done.

In other words, the true model that generates environmental damage is poorly known, and hence the decision maker should worry about potential model misspecification that is endogenous and may feed back on the state of the system.

3.3 The macroeconomics of climate change

As Harris et al. (2015) note, global climate change[8] is a major issue which worries

8 The issue often called **global warming** is more accurately referred to as **global climate change**, as this phenomenon will produce complex effects – with warming in some areas, cooling in others, and

policymakers worldwide. Widespread scientific acceptance of the reality of climate change is indicated in recent statements by the U.S. Global Research Program (2014, p. 7):

> Evidence for climate change abounds, from the top of the atmosphere to the depth of the oceans. Scientists and engineers from around the world have meticulously collected this evidence, using satellites and networks of weather balloons, thermometers, buoys, and other observing systems. Evidence of climate change is also visible in the observed and measured changes in location and behavior of species and functioning of ecosystems. Taken together, this evidence tells an unambiguous story: the planet is warming, and over the half century, this warming has been driven primarily by human activity.

In terms of economic analysis, GHG emissions, which cause planetary climate changes, represent both an environmental externality and the overuse of a common property resource. In particular, the atmosphere can be considered as a global public good into which individuals and firms can release pollution. In turn, global pollution creates a 'public bad' borne by all – a negative externality with a wide impact. In many countries, environmental protection laws limit the release of local and regional air pollutants. In these situations, in economic terminology, the negative externalities associated with local and regional pollutants have, to some degree, been internalized.

But, until recently, few controls existed for CO_2, the major greenhouse gas. The special characteristic of this global air pollutant is that it has no short-term damaging effects at ground level, but atmospheric accumulations of CO_2 and other GHGs will have significant permanent long-run effects on global temperature and weather, although there is big uncertainty about the probable scale and timing of these effects. The central problem here, as pointed out by Farid et al. (2016), is that no single firm or household has a significant effect on climate, yet collectively there is a huge effect. This means that pricing is necessary to force the internalization of climate effects into individual-level decisions. This pricing aligns private and social costs, thereby promoting cleaner and less energy use, and encouraging innovation toward these ends.

Scientists have modeled the effects of a projected doubling of accumulated CO_2 in the earth's atmosphere. Some of the predicted effects are: loss of land area, including beaches and wetlands, to sea-level rise; loss of species and forest area,

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generally increased variability in weather patterns.

including coral reefs and wetlands; disruption of water supplies to cities and agriculture; health damage and deaths from heat waves and spread of tropical diseases; increased costs of air conditioning; loss of agricultural output due to drought; and more. Some beneficial outcomes might include increased agricultural production in cold climates, lower heating costs, and fewer deaths from exposure to cold.

In addition to these effects, there are some other less predictable – but possibly more damaging – effects, including disruption of weather patterns, with increased frequency of hurricanes and other extreme weather events; a possible rapid collapse of the Greenland and West Antarctic ice sheets, which would raise sea levels by 12 meters or more, drowning major coastal cities; sudden major climate changes, such as a shift in the Atlantic Gulf Stream, which could change the climate of Europe to that of Alaska; positive feedback effects[9] such as an increased release of CO_2 from warming Arctic tundra, which would speed up global warming; and others.

As is obvious from the above, the effects of global climate change on economic activity are expected to be significant, although they are characterized by a high degree of uncertainty. For instance, temperature increases and other physical effects are expected to be translated into significant market impacts, with non-trivial output losses. These losses will come through effects on climate-sensitive sectors (for example, agriculture, forestry, coastal real estate, tourism). On the other hand, there are also non-market impacts, which include ecosystem disruption, health damages and water stress. In particular, the average impact from a 3 °C increase in temperature is expected to be about 2 percent of global GDP (see Farid et al., 2016). However, there is considerable variation across studies about this magnitude, a fact which simply reflects the high degree of uncertainty characterizing climate issues.

Vivid Economics (2013) identify nine dimensions along which climate change can have a macroeconomic impact. These dimensions refer to:

1. *Direct climate impacts*. The impact of climate change on the economy varies by sector; moreover a small subset of sectors is directly sensitive to the climate. The following sectors are typically the focus in economic studies: agriculture, forestry, energy, water, economic activities in coastal zones, health care and tourism. The non-market impacts of climate change are important, although measuring the value of non-market sectors can be difficult. A non-market item is one which is not traded in an economy, but

9 A **feedback effect** occurs when an original change in a system causes further changes that either reinforce the original change (positive feedback) or counteract it (negative feedback).

still has value to some agents in the economy. Biodiversity and cultural items are examples of non-market items; the change in health outcomes, mortality and morbidity is also a non-market impact often considered in the context of climate change. In a model, non-market items can be represented, via a measure of welfare, as having value in the same way as a market item does. Market and non-market values can be aggregated into GDP equivalent.

2. *The representation of cross-sectoral interactions*. Macroeconomic analysis is concerned with the wider impact of a direct shock and so the representation of interactions between sectors is important in order to capture indirect and higher-order effects. The set of indirect, higher-order effects is diverse. Examples include: direct impacts on agriculture that can change the terms of trade for economies in which agriculture generates a large proportion of income; changes in heating and cooling requirements that can change the price of energy, which affects all sectors that use energy as an input; direct health impacts that can affect labor productivity, which directly affects income and the productivity of all other sectors.
3. *Time*. Climate change is a dynamic process and thus static models will not capture all the effects.
4. *Growth*. Climate change may affect the growth rate of an economy by changing either output today or returns that may be earned in the future.
5. *Space*. The impacts of climate change differ by region and thus studies that do not consider a spatial dimension may not adequately describe the impact of climate change.
6. *Cross-border spillovers*. The impacts that climate change in one country have on other countries should be taken into account, including the effects on trade, financial flows and migration.
7. *Uncertainty*. A full picture of the macroeconomic impact of climate change must account for uncertainty about both climate and economy.
8. *Extreme weather*. Extreme weather events can be significant disasters with complex impacts that often appear large in the short term, but insignificant in the long term.
9. *Vulnerability and adaptation*. The role of adaptation is to reduce the vulnerability of an economy to the climate.

Regarding macroeconomic modeling, the effects of climate change could be analyzed using two basic approaches. The first is through the effect on factor stocks and productivity and the growth rates of both. For example, floods might damage infrastructure, or labor productivity might decline due to increased temperature. The second is through the effect on the way in which agents maximize their objectives. For example, demand for health care or air conditioning might increase, as might uncertainty over future states of the world, which affects how households plan. Another example is that climate change might affect non-market items that households value, such as biodiversity.

At this point, it may be useful to recall the causal chain linking economic behavior today to economic consequences tomorrow via climate change. The chain can be viewed as follows. First, economic activities generate emissions, which in turn lead to high concentrations of, for instance, CO_2. Second, this high concentration of CO_2 causes and – at the same time – accelerates climate change. Third, climate change has a negative impact on physical and ecological systems and, finally, on economies. Regarding policy, mitigation can consist of reducing emissions (or removing GHGs from the atmosphere) at the beginning of the chain in order to avoid or minimize climate change in the first place, whereas adaptation consists of responding to economic damages from climate change at the end of the chain.

Based on the above, macroeconomic policy is needed in order to deal with the impacts of climate change on economic activity. The content of macroeconomic policy should be designed and evaluated according to sustainability criteria alongside economic and social criteria. In the follow sections, we briefly discuss the macroeconomic policy instruments at the disposal of economic authorities for both mitigation and adaptation.

3.3.1 Available policy instruments for mitigation and adaptation

Two types of measures can be used to address climate change. On the one hand, mitigation or preventive measures tend to lower or mitigate the greenhouse effect. On the other hand, adaptive measures deal with the consequences of the greenhouse effect and try to minimize their impact.

Mitigation or preventive measures include: (a) Reducing emissions of GHGs. This can be achieved either by reducing the level of emissions-related economic activities, or by shifting to more energy-efficient and renewable energy technologies that allow the same level of economic activity at a lower level of CO_2 emissions. (b)

Enhancing carbon sinks. Forests and soils store carbon and recycle CO_2 into oxygen; preserving forested areas, expanding reforestation, and using carbon-storing agricultural techniques have a significant effect on net CO_2 emissions.

Adaptive measures include: (a) construction of dikes and seawalls to protect against rising sea level and extreme weather events such as floods and hurricanes; (b) shifting cultivation patterns in agriculture to adapt to changed weather conditions in different areas, and relocating people away from low-lying coastal areas; and (c) creating institutions that can mobilize the needed human, material and financial resources to respond to climate-related disasters.

Mitigation

It is both obvious and reasonable that strategies for reducing emissions will reflect countries' differing initial positions and political constraints and circumstances (see e.g. Farid et al., 2016). Regarding mitigation policies, the most common possibilities are: (a) carbon taxes, (b) tradable permits, and (c) subsidies, standards, research and development (R&D), technology transfer and other regulatory devices.

However, fiscal policies – and especially carbon taxes or emissions trading schemes (ETSs) with allowance auctions – are believed by the majority of economists to have two key advantages over regulatory approaches. The first advantage is that they are environmentally effective. Pricing carbon increases prices for fossil fuels, electricity, etc., thus promoting and striking the efficient balance across the entire range of mitigation opportunities. The latter include: replacing coal with (less carbon-intensive) natural gas in power generation, and shifting from these fuels to (zero-carbon) renewables and nuclear power; reducing the demand for electricity, transportation fuels and heating fuels through higher energy efficiency and less use of energy-consuming products; and so on. The second advantage is that they can raise significant revenues, creating space to reduce other taxes that create significant economic distortions. Regulations (for example, emission rate, energy efficiency and renewables standards) are believed to be less effective because they focus on a narrower range of mitigation opportunities. A combination of regulations is more effective, though not all opportunities can be exploited (for example, reductions in vehicle or air conditioner use), multiple programs are administratively complex, and implicit CO_2 prices typically vary considerably across sectors (an unintended distortion which means that the market is not left to achieve mitigation in the most efficient ways). Moreover, regulatory policies do not raise revenue.

In principle, the choice between carbon taxes and ETSs is less important than doing either and getting the design basics right. The most important factors are: to cover emissions comprehensively; to establish stable prices in line with environmental objectives; and to exploit fiscal opportunities. ETSs can be as efficient as carbon taxes, but thus far they have suffered from the following shortcomings: they have lacked full coverage, as they have focused on large industrial sources, omitting small-scale sources, for example, from vehicles and buildings; they require accompanying price stability provisions, such as price floors and ceilings, in order to provide the certainty over emissions prices needed to encourage low-emission investments; and they require auctioning of allowances (instead of giving them away for free) so that the resulting revenue can be used for broader fiscal reform.

An important aspect here has to do with the degree of international cooperation, which could serve to enhance mitigation efforts. As is discussed in greater detail in Chapter 8, international cooperation is challenging because of the reluctance of any country to mitigate unilaterally, since it bears the costs alone, while the climate benefits accrue to all countries, which is the well-known problem of **free riding**. The 1997 Kyoto Protocol – which set emissions reduction targets for individual countries in 2008, relative to 1990 levels – was largely ineffective. Key problems included lack of coverage (developing countries were not included and the United States did not ratify), the differing burdens of mitigation (depending partly on a country's emissions growth from 1990 to 2008), and the lack of enforcement (there were no penalties for noncompliant countries).

Adaptation

Adaptation policies complement mitigation and are largely in countries' own interests, but design specifics are highly dependent on national circumstances. Adaptation refers to deliberate adjustments in ecological, social and economic systems, in order to moderate adverse impacts of climate change and harness any beneficial opportunities (see Agrawala et al., 2011). Adaptation includes 'hard' policy measures (for example, dyke construction, changing crop varieties, adapting infrastructure) and 'soft' measures (for example, early warning systems, building codes, insurance). These measures might reduce the urgency of mitigation, but only moderately (for example, there are limits to how much we can protect against extreme climate outcomes). The benefits of adaptation are largely domestic, although there are potential cases of cross-border spillovers. Preventive actions are typically more cost effective, and more common, than reactive actions, but are hindered by uncertainties and, for developing economies, funding constraints. Economic aspects of adaptation policy have received much less attention from analysts than has mitigation, reflecting their strong dependency on country-specific circumstances and uncertainty over local climate impacts.

3.4 Monetary policy and climate change

The current unsustainable use of natural resources worldwide, as well as the related uncertainty about the consequent evolution of climate, poses risks for both the environment and the real economy. As already discussed, this uncertainty has triggered the creation of a large body of literature which studies both the potential effects of climate change but also the ways to moderate this trend (see e.g. Stern, 2007, CCISC, 2011). Nevertheless, little attention has been paid, thus far, to the implications of climate change for the conduct of monetary policy and the role of central banks.

It has been argued that, as a result of climate change and climate policy, macroeconomic developments could become less stable and economic growth could fluctuate considerably from year to year (see e.g. Nordhaus, 1991a, 1991b, 1991c, 2007, Xepapadeas, 2005, Stern, 2007, Brock et al., 2014). In such a case, monetary policymaking and implementation would become more challenging, in the sense that further policy actions, aiming at short-term output and employment stabilization, should be adopted. Moreover, in order to reduce GHG emissions and achieve a less carbon-intensive output structure, the relative prices of commodities would have to change (see e.g. Haavio, 2010). The cost of GHG emissions would have to rise, as would the price of fossil fuels and energy relative to other commodities and production inputs. Here, the key issue for central banks is how such a large change in relative prices can occur without pushing up the pace of increase in the general level of prices, i.e., causing higher inflation. What are the implications of such developments for inflation stabilization?

In general, it is therefore expected that environmental risks, and policies to mitigate them, will affect central banks' objectives and actions. In other words, nowadays central banks – and monetary authorities in general – face extra challenges. More specifically, in addition to their traditional role, which is inflation and output stabilization, and the use of unconventional policies to help promote economic recovery since the 2008 world shock, central banks also need to support environmental policy. This implies that central banks need to address long-term problems too.

Generally speaking, there are three types of climate-related risks and equivalently three major challenges for monetary policy (see e.g. Batten et al., 2016, Farid et al., 2016). These are physical risks, transition risks and liability risks. *Physical risks* arise from the interaction of climate-related hazards with the vulnerability of exposure of human and natural systems. They have the potential to trigger financial and macroeconomic instability. For instance, it could be expected that, as a result of physical risks, food prices could become more volatile, seasonal patterns in inflation rates could change, and finally potential growth could be affected. *Transition risks* are risks of economic dislocation and financial losses associated with a disorderly transition to a lower-carbon economy. For instance, increased reliance on bioenergy could increase the volatility of headline inflation rates, as both food and energy prices could react to the same weather-related shocks. *Liability risks* are risks that liability insurance providers could end up with large claims related to loss and damage arising from physical or transition risk from climate change. The increase in temperature and the economic catastrophes caused by climate change could reduce the profitability of firms and could deteriorate their financial position. Accordingly, debt defaults could arise which would lead to systemic bank losses. Lower firm profitability combined with global-warming-related damages could affect the confidence of investors, inducing a rise in liquidity preference and a fire sale of the financial assets issued by the corporate sector. It is possible that all the above risks could translate into increased (short-term) fluctuations in output, employment and prices.

Therefore, in light of the rather significant – although uncertain – effects of global climate change on economic activity, and the subsequent need to design macroeconomic policies to deal with these effects, there are at least two questions for monetary authorities to ask and answer.

1. First, can and should central banks respond to climate change, with the aim of controlling it or mitigating its effects in any specific way, or should this duty be left to other policy instruments, for instance to fiscal policy instruments?
2. Second, given the macroeconomic impacts of climate change, what is the best way to react using monetary policy?

With regard to the first question, it should be noted that there are two opposing factors at play. On the one hand, climate change does not appear to be the kind of cyclical development that central banks are used to dealing with, in terms of frequency and co-movement with other economic variables. On the other hand, the consequences that can so far be detected are dire enough to draw the attention of central banks. If climate change looks more like a trend, at least for the timeframe of monetary policy, this should call for limited action on the part of central banks. The tools at the disposal of central banks are more suitable for dealing with transitory, cyclical phenomena, than with longer-term ones. However, although it seems that climate change moves more like a trend than a cycle and that, for this reason, it is not something that monetary policy is equipped to deal with, its impact could become so high that it could not be ignored, even if – in the final analysis – other areas of economic policy are more suitable for confronting the problem.

Moreover, if monetary policy is believed to contribute directly to growth, and growth is associated with the emissions that cause the greenhouse effect, then part of those emissions could be moderated by the actions of central banks. The output gap component in this scheme could be environmentally adjusted so that monetary policy decisions incorporate their impact on the environment and, ultimately, on climate change. This may appear to be a very indirect channel, but it could be a manageable one for monetary policy – although at the cost of sacrificing growth, instead of aiming at the most direct and technological causes of global warming. However, this kind of control or mitigation that monetary policy could perform does not seem to be very efficient. As many others have already argued, the balance in terms of effective response to environmental challenges is tilted toward fiscal policy. Imposing taxes on, or defining caps to, activities that generate the most harmful GHG emissions seems to be the primary measure to be taken in this respect.

In addition, setting up markets in which emissions can be effectively traded would also seem to be a step in the right direction. The idea is for productive activities to internalize the costs generated by the emission of GHGs or other forces behind climate change. Industrial policy, whose importance cannot be underestimated in developing economies, can also help a great deal by favoring the development of greener technologies. In the face of this, the impact of monetary policy seems fairly limited. Summing up so far, climate change as we conceive it today does not seem to be the kind of cyclical episode that monetary policy is most suited to deal with; the way in which it could regulate emissions caused by higher economic activity (through monetary tightening) seems too far from the 'fine tuning' role of monetary policy. In this respect, fiscal and development policy appear to be better suited to deal with climate change.

With regard to the second question, and especially in order to assess – given the macroeconomic impacts of climate change – what the appropriate monetary policy to deal with these impacts is, we should first try to understand the nature of climate change as an economic shock. Perhaps the best way to envision climate change from the point of view of a central banker is 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.[10] The more persistent these shocks are, the higher the chances are that they will lead to a permanent reduction in potential output, affecting not only 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. Furthermore, climate change can have significant effects on trade, capital flows and migration, as well as on investment and savings. Hence, again, the output gap component could be environmentally adjusted so as to take into account the macroeconomic impacts of climate change, and therefore direct monetary policy decisions in incorporating this impact.

With respect to the effects of climate change, especially on prices, Haavio (2010) claims that climate policy may have two types of effects. The first group of effects is what can generally be classified as direct effects. The introduction of stricter climate policy pushes up the price of fuels and energy. At the same time, the price of both passenger and freight transport services also rises and energy-intensive industrial goods become more expensive. Monetary policy should not respond to these direct effects, since a prerequisite of a successful climate policy is just such a rise in the relative prices of carbon-intensive products and production inputs. In addition, climate can also have indirect effects on the general level of prices. Rising energy and fuel prices erode consumers' purchasing power. If people attempt to restore the purchasing power of their income to the level it was prior to the rise in energy and fuel prices, wages and prices could also rise in those parts of the economy in which the higher energy and fossil fuel prices would not by themselves increase costs. This could then lead to a self-sustaining spiral of rising costs and prices. These indirect effects are something that a central bank should be able to prevent. Hence, as Haavio concludes, the question that naturally arises is what is required of monetary policy in order for the direct effects of climate policy to pass through into prices while being able to avoid the indirect effects.

10 Supply shocks due to climate change may be either negative or positive, depending on each region or country; available estimates, however, suggest that their global effect is likely to be negative (see Mendelsohn et al., 2000, Nordhaus and Boyer, 2000).

To sum up, we expect that the importance of the central banks in the design of coupled economic and climate change policies will increase considerably in the future, for two main reasons. The first is, as discussed above, the need to stabilize the economy and promote growth by taking into account potential climate change damages to output, along with climate policies related to mitigation and adaptation. The second relates to the need to provide an efficient framework for the financing of climate change policies. This is important, in view of the recent Paris COP 21 agreement which states that: "Developed country Parties shall provide financial resources to assist developing country Parties with respect to both mitigation and adaptation in continuation of their existing obligations under the Convention" (UNFCCC, 2015, p. 26) and recognizes "the urgent need to enhance the provision of finance, technology and capacity-building support by developed country Parties, in a predictable manner, to enable enhanced pre-2020 action by developing country Parties" (p. 2).

3.4.1 Dynamic stochastic general equilibrium models and monetary policy

As Christiano et al. (2011) point out, there has been enormous progress in recent years in the development of dynamic stochastic general equilibrium (DSGE) models for the purpose of monetary policy analysis (see e.g. Leeper, 1991, Schmitt-Grohe and Uribe, 2005, 2007, Leith and Wren-Lewis, 2008, Kirsanova et al., 2009, Leeper et al., 2009, 2010, Philippopoulos et al., 2015, 2017). These models have been shown to fit aggregate data well by conventional econometric measures. For example, they have been shown to do as well or better than simple atheoretical statistical models at forecasting outside the sample of data on which they were estimated. In part because of these successes, a consensus has formed around a particular model structure, the new Keynesian model, in which there is a real role for monetary policy, or in other words, money matters to real variables. This is the context used by all central banks including the European Central Bank.

Gali (2015) notes that the new Keynesian modeling approach combines the DSGE structure characteristic of RBC models with assumptions that depart from those found in classical monetary models (see also Wickens, 2008, p. 206). In particular, the key elements and properties of the basic new Keynesian model[11] are:

(a) *Monopolistic competition*. Prices and/or wages are set by private economic agents in order to maximize their objectives, instead of being determined by an

11 See also Gali and Gertler (2007) for a discussion of the main features of the new Keynesian model.

anonymous Walrasian auctioneer seeking to clear all markets.

(b) *Nominal rigidities*. Firms are subject to constraints on the frequency with which they can adjust the prices of the goods they sell, or they face costs of adjusting those prices.

(c) *Short-run non-neutrality of monetary policy*. As a consequence of the presence of nominal rigidities, changes in short-term nominal interest rates are not matched by one-for-one changes in expected inflation, thus leading to variations in real interest rates.

Note here that, as Gali (2015) points out, due to the presence of nominal rigidities (i.e., feature (b)) – which is required in order for monetary policy to matter for real variables (i.e., feature (c)) – firms, in order to be able to change prices and in order to be able to set prices in the first place, require a degree of market power. This justifies the presence of imperfect competition – feature (a) – which is why typical new Keynesian models make these two assumptions, namely monopolistic competition and nominal rigidities, jointly.

In the following sections we briefly present some simple mechanisms though which market imperfections and price stickiness are introduced into DSGE models, as well as some simple rules governing the conduct of monetary policy.

Market imperfections

The most common way in which market imperfections are introduced into DSGE models is by assuming monopolistic competition in the product markets. To do so, the relatively simple, and hence attractive from an algebraic point of view, Dixit-Stiglitz (1977) framework is usually adopted (see, among many others, Schmitt-Grohe and Uribe, 2007, Christiano et al., 2011). In particular, it is usually assumed that gross output in the economy, denoted by Y_t, is produced by a representative, competitive firm using the following technology:

$$Y_t = \left(\int_0^1 Y_{i,t}^{\frac{1}{\lambda_f}} di \right)^{\lambda_f}, \lambda_f > 1, \tag{3.16}$$

where λ_f shows the degree of substitution between the different intermediate inputs, $Y_{i,t}$. The representative firm takes the price of gross output, P_t, and the price of intermediate inputs, $P_{i,t}$, as given. Profit maximization leads to the first-order condition:

$$Y_{i,t} = Y_t \left(\frac{P_{i,t}}{P_t} \right)^{-\frac{\lambda_f}{\lambda_f - 1}}. \quad (3.17)$$

Combining equations (3.16) and (3.17) gives the following relationship between the aggregate price level and the prices of the intermediate goods:

$$P_t = \left(\int_0^1 P_{i,t}^{-\frac{1}{\lambda_f - 1}} di \right)^{-(\lambda_f - 1)}.$$

Here the i^{th} intermediate good is produced by a single monopolist, who takes equation (3.17) as its demand curve. The value of λ_f determines how much monopoly power the i^{th} producer has. If, for instance, $\lambda_f = 1$, then product markets are perfectly competitive.

Price stickiness

Price stickiness can be introduced into DSGE models in various ways. Following Wickens (2008), we focus on three theories used in modern macroeconomics: (i) the overlapping contracts model of Taylor (1979), in which wages are the main cause of price change; (ii) the staggered pricing model of Calvo (1983), in which price changes occur randomly; and (iii) the optimal dynamic adjustment model used, for example, by Rotemberg (1982), in which the speed of adjustment is chosen optimally.

Taylor's model. This model is based on the following assumptions. (a) Price is a markup over marginal cost and the markup may be time-varying and affected in the short run mainly by the wage rate. (b) The wage rate at any point in time is an average of wage contracts that were set in the past but are still in force, and of those set in the current period. (c) When they were first set, wage contracts were profit maximizing and reflected the prevailing marginal product of labor and the expected future price level. The above-mentioned characteristics of Taylor's model, together with the assumption that wage contracts last longer than n periods, result in a price equation of the form:

$$p_t = \sum_{s=1}^{n-1} \alpha_s E_t p_{t+s} + \sum_{s=1}^{n} \beta_s E_t p_{t-s} + \frac{1}{n} \sum_{s=0}^{n-1} z_{t-s} + \nu_t + \xi_t,$$

where β is the discount factor, ν_t and ξ_t are the price markup over costs and a linear combination of innovations in price respectively, and z_t is the logarithm of the marginal product of labor. Therefore ξ_t is serially correlated. For each additional period, there is an extra forward-looking and lagged price term and an additional lag in productivity.

The Calvo model. This is perhaps the most popular pricing model as it offers a simple way to derive a theory of dynamic behavior of the general price level while starting from a disaggregated theory of prices. The general price level is the average price of all firms. It is assumed that firms are forward-looking and that they forecast what the optimal price, $p^*_{t+s}(s \geq 0)$ ≥ – which is the same for all firms – should be both in the future and in the current period. However, not all firms are able to adjust to the optimal price immediately and that adjustment, when it does occur, is exogenous to the firm and happens randomly. It is also assumed that in any period there is a given probability ρ of a firm being able to make an adjustment to its price. When firms do adjust their price, they set it to minimize the present value of the cost of deviations of the newly adjusted price $p^\#_t$ from the optimal price. In this setup, inflation is given by:

$$\pi_t = \rho(1-\gamma)(p^*_t - p_{t-1}) + \gamma E_t \pi_{t+1}, \tag{3.18}$$

where β is the discount factor and $\gamma = \beta(1-\rho)$. Equation (3.18) states that the actual change in price is related to the 'desired' change in price, $p^*_t - p_{t-1}$, and to the expected future change in price. In the steady state, the actual price level equals the desired level and inflation is zero.

Optimal dynamic adjustment. This theory assumes two types of distortion. The first one arises because changing prices is costly, whereas the second one is the cost of being out of equilibrium. The trade-off is expressed in terms of an intertemporal cost function involving the change in the logarithm of the price level, Δp_t , and deviations of the price level from its optimal long-run price, p^*_t. Minimization of this cost function implies that:

$$\pi_t = \frac{\alpha}{1+\alpha}(p^*_t - p_{t-1}) + \frac{\beta}{1+\alpha} E_t \pi_{t+1},$$

where α is the relative cost of being out of equilibrium, and β is the discount factor. The greater α is, the larger is the coefficient on 'desired' inflation rate, $p^*_t - p_{t-1}$. The greater β is, the larger is the coefficient of future expected inflation.

Simple monetary policy rules and the conduct of monetary policy

Let us clarify, first of all, that in order to study the conduct of monetary policy, it is not a prerequisite to explicitly incorporate money into the relevant model. Following most of the recent literature, the only explicit role played by money can be to serve as a unit of account. In that case, whenever monetary policy is specified in terms of an interest rate rule, no reference whatsoever needs to be made to the quantity of money in circulation in order to determine the economy's equilibrium. However, when the specification of monetary policy involves the money supply, we can either postulate a 'conventional' ad-hoc money demand equation in order to close the model, or we can introduce an explicit role for money by assuming, for instance, that real balances generate utility to households. Obviously, in the latter case, the derived money demand function is microfounded.[12]

Regarding the conduct of monetary policy, most of the relevant literature assumes that the policy tool available to the monetary authorities is the short-term nominal interest rate on risk-free government bonds (see, for instance, the survey paper by Christiano et al., 2011, as well as the papers on monetary policy analysis mentioned in the beginning of Section 3.4.1). Moreover, in most of these papers, the interest rate is set according to a simple feedback rule belonging to the class of Taylor-type rules (Taylor, 1993). Taylor finds that a very simple rule does a good job of describing Federal Reserve interest-rate decisions, particularly those since 1982. Taylor's rule is given by the expression:

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

where 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, and ε_t is a random variable. Taylor (1999) sets $\alpha = 1.5$ and $\gamma = 0.5$ or 1, and uses this equation to interpret Federal Reserve behavior over several eras since 1960. For generalized versions of the Taylor rule, see for example Davig and Leeper (2007).

Schmitt-Grohe and Uribe (2007) use a variant of the Taylor rule and assume that the short-term nominal interest rate in their model is set as:

$$\ln(R_t / R^*) = \alpha_R \ln(R_{t-1} / R^*) + \alpha_\pi E_t \ln(\pi_{t-i} / \pi^*) + \alpha_y E_t \ln(y_{t-i} / y^*), i = -1, 0, 1 \quad (3.19)$$

where y^* denotes the non-stochastic Ramsey-steady-state level of aggregate demand and $R^*, \pi^*, \alpha_R, \alpha_\pi$ and α_y are parameters. The index i can take three values: $-1, 0$ and 1. As Schmitt-Grohe and Uribe point out, when $i = 1$ they refer to the interest-rate rule as backward looking, when $i = 0$ as contemporaneous, and when $i = -1$ as

12 For a discussion of the role of money in new Keynesian models, see e.g. Gali (2015) and the references cited therein.

forward looking. Intuitively, equation (3.19) states that the nominal interest rate at time t is characterized by persistence, since it depends linearly on its own lag, and reacts to inflation and the output gap as indicated by the last two terms on the right-hand side of (3.19).[13]

Christiano et al. (2011) assume that monetary policy, when linearized around the steady state, is characterized by the following simple Taylor-type rule:

$$R_t = r_\pi E_t \pi_{t+1} + r_x x_t,$$

where R_t denotes the percentage deviation of the interest rate in period t from its steady-state value, $E_t \pi_{t+1}$ denotes the expected percentage deviation of the inflation rate in period $t+1$ from its steady-state value, x_t denotes the output gap in period t, and r_π and r_x are parameters.

3.5 Climate change and central banks

As mentioned previously, to assess and quantify the effects of environmental risks on monetary policymaking, we need IAMs that are capable of accounting for, as well as of quantifying, such effects. Hence, one way forward is to construct dynamic stochastic general equilibrium integrated assessment models (DSGE IAMs) in which not only will the effects of various environmental risks (such as sea level rise and destabilization of polar ice sheets, loss of ecosystem services and biodiversity, health issues, increase in the frequency of extreme weather events, change in precipitation patterns and loss of agricultural production) be incorporated, but also the effects of climate policies aiming to mitigate the detrimental effects of climate change, or to adapt to climate change. In such models, in addition to 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.

3.5.1 The role of the central bank

By incorporating a central bank into the above model structure, economic policy will have a richer and wider set of policy instruments at its disposal. In other words, apart from carbon taxes, emission limits, tradable emission permits and others, economic policy conducted by the central bank could also use the money stock or the market

13 Schmitt-Grohe and Uribe (2005) use a similar interest rate rule in which they allow the interest rate to react also to the wage inflation.

nominal interest rate (or even the funds rate, open market operations, and so forth, in a richer model setup) to affect and stabilize the macroeconomy, stabilize emissions, design efficient adaptation strategies, and 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, the new Keynesian tradition should be followed in which it is assumed that product markets are not perfectly competitive and prices are sticky, at least temporarily. In particular, it is assumed that there are market imperfections, using the Dixit-Stiglitz (1977) context (meaning that there is monopolistic competition in product markets), and price stickiness either á la Rotemberg (meaning that firms face a convex cost of price adjustment), or á la Calvo.[14] Following most of the related monetary policy literature (see e.g. Schmitt-Grohe and Uribe, 2007), feedback policy rules should be considered. For instance, monetary policy can be used in a standard Taylor-type fashion, such as the one described in Section 3.4.1.

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14 See, for example, Schmitt-Grohe and Uribe (2004a, p. 200, and 2004b). For a review of the literature on models of price stickiness (Taylor-type, Calvo-type and Rotemberg-type), see e.g. Wickens (2008, Chapter 9.4).

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4 Climate Change Policies: Mitigation

Climate change policies have evolved in terms of both theoretical foundations and applications. At this stage, as shown in Figure 4.1, three types of policies emerge: mitigation, adaptation and solar radiation management (SRM). Mitigation and adaptation are the standard policies in theory and practice, while SRM is still at the level of theoretical analysis.

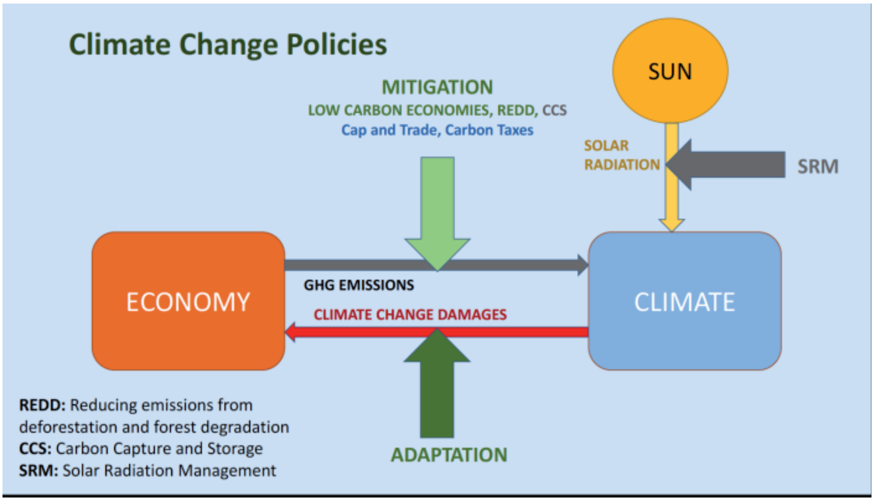

Figure 4.1. Climate change policies

In designing mitigation and adaptation policies, an important tool is the so-called representative concentration pathways.

4.1 Representative concentration pathways

Representative concentration pathways (RCPs), which have been developed by the IPCC (2013), are scenarios that include time series of emissions and concentrations of the full suite of GHGs and aerosols and chemically active gases, as well as land use/land cover. The word 'representative' signifies that each RCP provides only one of many possible scenarios that would lead to the specific radiative forcing characteristics. The term 'pathway' emphasizes that not only are the long-term concentration levels of interest, but also the trajectory to reach long-term outcomes.

RCPs usually refer to the portion of the concentration pathway extending up to the year 2100, for which IAMs produced corresponding emission scenarios. Extended concentration pathways describe extensions of the RCPs from 2100 to 2500 that were calculated using simple rules generated by stakeholder consultations, and do not represent fully-consistent scenarios. Four RCPs produced from IAMs were selected from the published literature and are used in the IPCC (2013) assessment as a basis for the climate predictions and projections:

- RCP2.6. One pathway where radiative forcing peaks at approximately 3 Wm^2 before 2100, and then declines for the corresponding extended concentration pathway, assuming constant emissions after 2100.
- RCP4.5 and RCP6.0. Two intermediate stabilization pathways in which radiative forcing is stabilized at approximately 4.5 Wm^2 and 6.0 Wm^2 respectively after 2100 (the corresponding extended concentration pathways), assuming constant concentrations after 2150.
- RCP8.5. One high pathway for which radiative forcing reaches a level greater than 8.5 Wm^2 by 2100 and continues to rise for some time, assuming constant emissions after 2100 and constant concentrations after 2250.

These RCPs represent a larger set of mitigation scenarios and were selected to have different targets in terms of radiative forcing in the year 2100 (about 2.6, 4.5, 6.0 and 8.5 Wm^2). The scenarios should be considered plausible and illustrative, and do not have probabilities attached to them. The four RCPs were developed using IAMs that typically include economic, demographic, energy and simple climate components.

General results obtained from the RCPs indicate that:

- In all RCPs, atmospheric CO_2 concentrations are higher in 2100 relative to the present day as a result of a further increase in cumulative emissions of CO_2 in the atmosphere during the twenty-first century.
- Global surface temperature change at the end of the twenty-first century is likely to exceed 1.5 °C relative to 1850-1900 for all RCP scenarios except RCP2.6. It is likely to exceed 2 °C for RCP6.0 and RCP8.5, and more likely

than not to exceed 2 °C for RCP4.5. Warming will continue beyond 2100 under all RCP scenarios except RCP2.6. Warming will continue to exhibit interannual-to-decadal variability and will not be regionally uniform.

Some of these results are summarized in the information presented in Figures 4.2–4.4 and Table 4.1, from IPCC (2013). Figure 4.2(a) depicts the time paths of the mean global average surface temperature, while Figure 4.2(b) shows the extent of September sea ice in the Northern Hemisphere for each of the four RCP scenarios. The declining path of the sea ice extent is a clear indication of the effects of global warming.

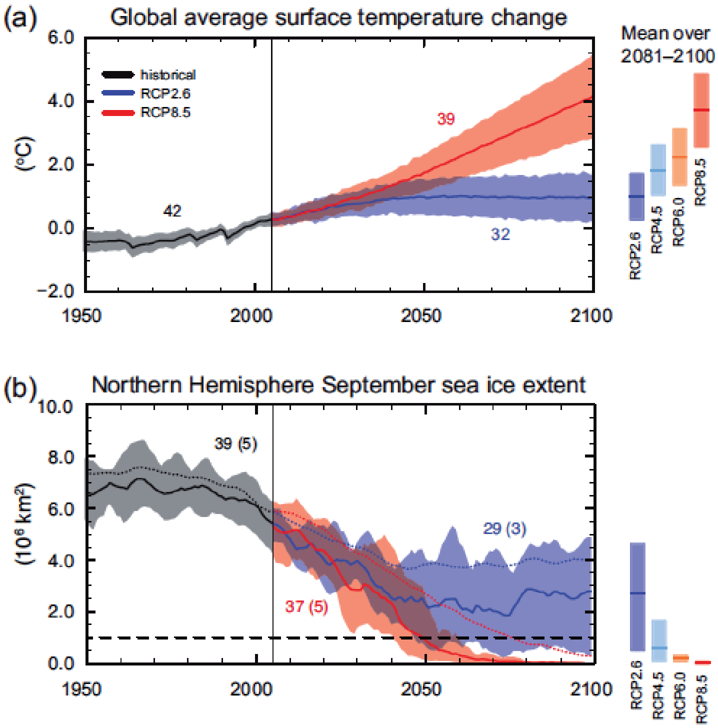

Figure 4.2. Global average temperature change and sea level extent

Source: IPCC, 2013, *Climate Change 2013: The Physical Science Basis*, Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge, UK and New York, NY: Cambridge University Press, Figure SPM.7.

Similar information, including sea level rise, is reported in Table 4.1.

Table 4.1. Likely ranges of global mean surface temperature change and sea level rise

		2046–2065		2081–2100	
	Scenario	Mean	*Likely* range[c]	Mean	*Likely* range[c]
Global Mean Surface Temperature Change (°C)[a]	RCP2.6	1.0	0.4 to 1.6	1.0	0.3 to 1.7
	RCP4.5	1.4	0.9 to 2.0	1.8	1.1 to 2.6
	RCP6.0	1.3	0.8 to 1.8	2.2	1.4 to 3.1
	RCP8.5	2.0	1.4 to 2.6	3.7	2.6 to 4.8
	Scenario	Mean	*Likely* range[d]	Mean	*Likely* range[d]
Global Mean Sea Level Rise (m)[b]	RCP2.6	0.24	0.17 to 0.32	0.40	0.26 to 0.55
	RCP4.5	0.26	0.19 to 0.33	0.47	0.32 to 0.63
	RCP6.0	0.25	0.18 to 0.32	0.48	0.33 to 0.63
	RCP8.5	0.30	0.22 to 0.38	0.63	0.45 to 0.82

Source: IPCC, 2013, *Climate Change 2013: The Physical Science Basis*, Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge, UK and New York, NY: Cambridge University Press, Table SPM.2.

The paths of global mean sea level rise corresponding to each RCP are shown in Figure 4.3.

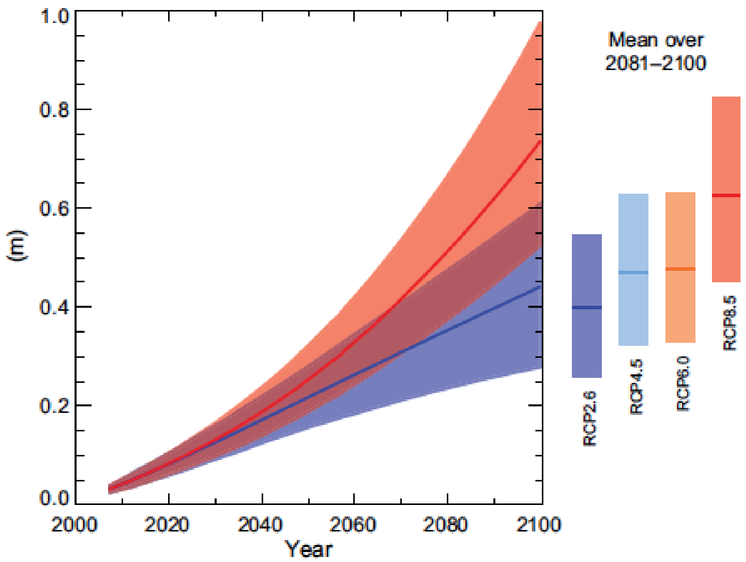

Figure 4.3. Global mean sea level rise

Source: IPCC, 2013, *Climate Change 2013: The Physical Science Basis*, Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge, UK and New York, NY: Cambridge University Press, Figure SPM.9.

Figure 4.4 depicts cumulative CO_2 emissions, starting from 1870 and projected up to the year 2500.

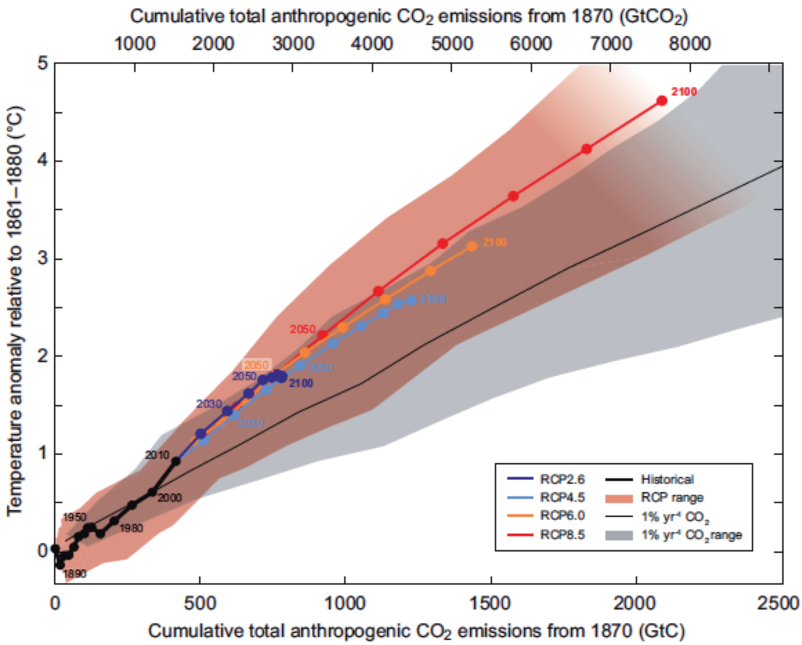

Figure 4.4. Cumulative anthropogenic CO_2 emissions: Historical data and projections

Source: IPCC, 2013, *Climate Change 2013: The Physical Science Basis*, Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge, UK and New York, NY: Cambridge University Press, Figure SPM.10.

Typical output produced by IAMs and optimizing models which shows global mean temperature paths (the temperature anomaly) can be found in, for example, DICE-2013R and Golosov et al. (2014).

4.2 Carbon budgeting

If we use as a basis for policy design the proportionality relationship between the global temperature anomaly and the cumulative carbon emissions, the concept of the carbon budget emerges. A **carbon budget** indicates the amount of emissions that can be released from the current period to the future which, given the amount of emissions which have already been released from the pre-industrial period up to the present, will not exceed a target temperature increase.

The carbon quota for a 66 percent chance to keep below the 2 °C target is shown in Figure 4.5 (Global Carbon Project, 2016).

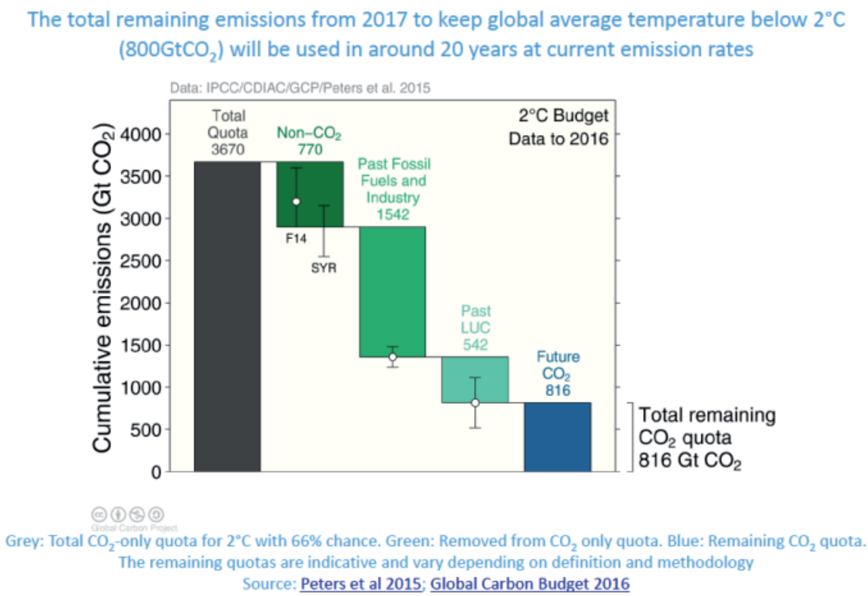

Figure 4.5. Carbon quota for the 2 °C

Source: The Global Carbon Project, 2016. Reproduced under Creative Commons Attribution 3.0 License, available at https://creativecommons.org/licenses/by/3.0/.

In terms of policy design, the concept of a carbon budget is useful. It is, however, a first step, because in order to implement the policy, two major issues need to be resolved.

1. How will the remaining quota of 816 $GtCO_2$ be allocated among nations? This needs to be resolved by international negotiations and agreements which are discussed analytically in Chapter 8.

2. Once the allocation is determined, climate change policies – whether national or international – need to be determined so that markets will produce the desired level of global emissions.

4.3 The social cost of carbon and carbon taxes

4.3.1 The social cost of carbon

The **social cost of carbon** (SCC) represents the economic cost caused by an additional ton of CO_2 emissions (or carbon) or its equivalent. More formally, the marginal SCC reflects the future damage of incremental GHG emissions. It is important for policy purposes, because it gives us an understanding of where carbon prices (or GHGs prices more generally) should be.

The SCC at time *t* is defined by:

- The marginal social utility of consumption at *t* (embodying ethical values and a particular path),
- The impact on consumption at *t* of all relevant preceding temperature changes (and resultant climate change),
- The impact on a relevant temperature increase of increases in preceding carbon stocks,
- The impact on all relevant stocks of an increase in carbon emissions at *t*, where 'impact' in the above is to be interpreted as a partial derivative.

Thus the SCC is:

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

where $U(C)$ is utility of consumption C; T is global average temperature; S is stock of GHGs; E is emissions of GHGs; and ρ is utility discount rate.

Nordhaus and Sztorc (2013) provide 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:

$$SCC(t) = -\frac{\partial W / \partial E(t)}{\partial W / \partial C(t)}. \quad (4.1)$$

The numerator is the marginal impact of emissions at time *t* on welfare, while the denominator is the marginal welfare value of a unit of aggregate consumption in period *t*. The ratio calculates the economic impact of a unit of emissions in terms of *t*-period consumption as a numeraire. In actual calculations, a discrete approximation of equation (4.1) is used. Note that the SCC is time-indexed. This indicates that the marginal cost of emissions at time t (in terms of consumption at time t as a numeraire) changes over time.

Nordhaus (2014) estimates the SCC using the DICE model in the following way. A base path of GHG emissions along with a base path of a comprehensive measure of economic welfare, which in this case is generalized consumption, is chosen. An increment of emissions in the second period of this path will generate an alternative path of consumption (see Nordhaus, 2014, Figure 1). The SCC is estimated by the difference in the present value of consumption between the two paths, discounted at an appropriate social discount rate (see Chapter 7, Section 7.1.1) in period 2, divided by the increment in emissions. That is,

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

Results from the DICE-2013R regarding global SCC are shown in Table 4.2 (Nordhaus, 2014). The sensitivity of the SCC estimates to the choices of the social discount rate is very clear.

Table 4.2. Estimates of the SCC according to policy and choice of discount rate

Global social cost of carbon under different assumptions					
Scenario	2015	2020	2025	2030	2050
Base parameters					
Baseline [a]	18.6	22.1	26.2	30.6	53.1
Optimal controls [b]	17.7	21.2	25.0	29.3	51.5
2 °C limit damage function					
Maximum [b]	47.6	60.1	75.5	94.4	216.4
Max of average [b]	25.0	30.6	37.1	44.7	87.9
Stern Review discounting					
Uncalibrated [a]	89.8	103.7	117.4	131.3	190.0
Calibrated [a]	20.7	25.0	30.1	35.9	66.9
Alternative high discount [a]	6.4	7.7	9.2	10.9	19.9

Notes: The social cost of carbon is measured in 2005 international US dollars. The years in the first row 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.

[a] Calculation along the reference path with current policy.

[b] Calculation along the optimized emissions path.

Source: Nordhaus, 2014, Table 1.

Results regarding the regional breakdown of the SCC are shown in Table 4.3 (Nordhaus, 2014).

Table 4.3. Regional estimates of the SCC according to different IAMs

Region	Emissions (billion tons CO_2 , 2005)	SCC 2015	Percent of global SCC RICE 2010 (U)	FUND 2013	PAGE 2011
United States	6.11	1.94	10	17	7
European Union	4.14	2.32	12	24	9
Japan	1.28	0.43	2	3	NA
Russia	1.54	0.18	1	10	NA
Eurasia	0.92	0.16	1	NA	NA
China	6.14	3.02	16	8	11
India	1.48	2.21	12	5	22
Middle East	2.14	1.89	10	NA	NA
Africa	0.69	2.09	11	6	26
Latin America	1.54	1.30	7	NA	11
OHI	1.93	0.74	4	NA	NA
Other	1.38	2.29	12	NA	NA
Weighted country average		1.92			
Global	29.30	18.60	100	100	100

Notes: This table distributes the global SCC by region. It uses the global estimate of the SCC from DICE-2013R and the regional distribution from RICE-2010. The weighted country average is the average of the country-specific SCCs. The results from other studies indicate that the regional distribution is poorly understood. FUND results are from Anthoff (2013) and PAGE results are from Hope (2011). Note that the regions do not always conform exactly across the models. OHI = other high-income countries. NA = not available.

Source: Nordhaus, 2014, Table 2.

In a climate model where a fully-optimal climate policy is determined, the SCC coincides with the optimal price of the climate externality and the optimal carbon tax.

Greenstone et al. (2011) provide an analysis of the alternative estimates of the SCC used in the US. They find, using DICE, PAGE and FUND to generate a distribution for the SCC, that the concentration of SCC values is between US$10-30 per ton CO_2.

Greenstone et al. (2011) also calculate the sensitivity of the SCC to the discount rate for different IAMs and socioeconomic scenarios, as shown in Table 4.4.

Table 4.4. The SCC and the discount rate for 2010 (in 2007 dollars)

Model	Socioeconomic reference scenario	Discount rate 5% Mean	3% Mean	2.5% Mean	3% 95th %ile
DICE	IMAGE	10.8	35.8	54.2	70.8
	MERGE	7.5	22.0	31.6	42.1
	Message	9.8	29.8	43.5	58.6
	MiniCAM	8.6	28.8	44.4	57.9
	550 ppm average*	8.2	24.9	37.4	50.8
PAGE	IMAGE	8.3	39.5	65.5	142.4
	MERGE	5.2	22.3	34.6	82.4
	Message	7.2	30.3	49.2	115.6
	MiniCAM	6.4	31.8	54.7	115.4
	550 ppm average*	5.5	25.4	42.9	104.7
FUND	IMAGE	-1.3	8.2	19.3	39.7
	MERGE	-0.3	8.0	14.8	41.3
	Message	-1.9	3.6	8.8	32.1
	MiniCAM	-0.6	10.2	22.2	42.6
	550 ppm average*	-2.7	-0.2	3.0	19.4

Notes: *Average of the GDP, population, and emission trajectories implied by the IMAGE, MERGE Optimistic, MESSAGE, and MiniCAM models under the 550 ppm CO_2eq full participation, not to exceed, stabilization scenario considered by EMF-22.

Source: Greenstone et al., 2011, Table 3.

Ackerman and Stanton (2010) point out that estimates of the SCC by the US government tend to be very low due to specific choices in parameters.

4.3.2 Carbon taxes

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

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

where E_t is emissions at time t; S is the stock of GHGs; and F is the production function including climate damages. It is shown that the externality price is equal to the optimal Pigouvian carbon tax. If the tax proceeds are rebated lump-sum to the representative consumer, then the competitive equilibrium allocation coincides with the solution of the social planner's problem. Optimal tax calculations, however, are very sensitive to the choice of the discount rate. Nordhaus (2008), using 1.5% as the utility discount rate, suggests \$30 per ton coal, while Stern (2007), using 0.1%, suggests \$250 per ton coal. Golosov et al. (2014) suggest \$56.90/ton and \$496/ton respectively for the two values of the discount rate.

In practice, carbon taxes are not widespread and the major instrument used is cap-and-trade policies. This is true despite the fact that they are regarded as either equivalent to cap-and-trade policies (Stavins, 2008), or as having some advantages to cap-and-trade policies on the grounds of preventing price volatility (Goulder and Schein, 2013). Some examples of carbon taxes in practice, which can be found in the OECD (2017) database on policy instruments for the environment (https://pinedatabase.oecd.org), are provided below.

- In 2012, Australia introduced a carbon-pricing mechanism for measured CO_2 emissions of emission-intensive, trade-exposed industries at the rate of €0.8501 per ton of CO_2 emissions. The revenues were 100 percent earmarked to support jobs and competitiveness in emissions-intensive, trade-exposed industries, clean technologies, renewable energies, energy efficiency, low-income households, farmers and biodiversity. The tax was abolished in 2014. Australia conducts climate change policy using tradable permit schemes.
- In 2008, Canada introduced the British Columbia carbon tax, which was revised in 2011. Revenues raised by the carbon tax, estimated to total \$1,849 million over the initial three years, are to be used to reduce personal and corporate income tax rates.
- In 1994, Denmark introduced a duty on CO_2. In the revision of 2012, tax rates were increased; no earmarking has been reported.
- In France, in the last revision of the domestic tax on carbon tax in January 2014, a carbon component (€7/tCO_2 in 2014, €14.5/tCO_2 in 2015 and €22/tCO_2 in 2016) was introduced with suppression of the exemption for households.
- In 1991, Norway introduced a CO_2-tax on mineral products. The tax was revised in 2017. In this revision several tax rates have been increased in real

terms. Tax rates on mineral oil used in domestic aviation were increased in line with the expected rate of inflation. Some examples of the tax rates are: €0.1342 per liter for diesel, heavy fuel oil and light fuel oil; and €0.1006 per sm3 for natural gas.

- In 2001, the United Kingdom introduced a Climate Change Levy which was revised in 2013. In the revision, tax rates were increased in line with the expected rate of inflation for 2013/14. The carbon price floor (CPF) came into effect on 1 April 2013. The CPF is a tax on fossil fuels used in the generation of electricity, achieved through changes to the existing Climate Change Levy regime in the case of gas, solid fuels and liquefied petroleum gas used in electricity generation. The CPF for electricity production from coal and other solid fuels is €0.5403 per gross gigajoule, while for electricity production from natural gas it is €0.0011 per kWh.

4.4 Other mitigation policies

The McKinsey bottom-up approach (Enkvist et al., 2007) analyzes the cost of a large number of mitigation policies. They show that insulation and fuel efficiency policies have net economic benefits (negative abatement costs), while policies such as forestation or carbon capture and storage have abatement costs up to €40 per ton CO_2.

In the following sections, we elaborate on two policies: carbon capture and storage, and REDD+.

4.4.1 Carbon capture and storage

The capture of CO_2 at the point of emission from coal- or gas-burning power plants is an attractive route to reducing CO_2 emissions into the atmosphere. To commercialize carbon capture, as well as transport of liquefied CO_2 and its storage in exploited oil fields or saline formations, many technological, commercial and political hurdles remain to be overcome. Urgent action is required if carbon capture and storage is to play a large role in limiting climate change. In Haszeldine (2009), there is a diagrammatic representation of the life-cycle chain of fossil fuel use, CO_2 separation and capture at power plants, and storage of CO_2 in porous rock deep below the ground.

4.4.2 Reducing Emissions from Deforestation and Forest Degradation

Reducing emissions from deforestation and forest degradation, and enhancing forest carbon stocks in developing countries (REDD+) can, according to proponents, generate large, cheap and quick reductions in global GHG emissions. The international community can achieve this by paying forest owners and users – either through national governments or directly – to fell fewer trees and manage their forests better. Farmers, companies and forest owners can simply sell forest carbon credits and reduce forest-related outputs. Activities in a REDD+ mechanism (Angelsen and Wertz-Kanounnikoff, 2008) are shown in Figure 4.6.

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

Figure 4.6. Activities in a REDD+ mechanism

Source: Angelsen and Wertz-Kanounnikoff, 2008.

The core idea of REDD+ is to create a multilevel (global-national-local) system of payments for environmental services (PES) that will reduce emissions and increase forest carbon stocks. While payment directly to forest carbon rights holders (forest owners and users) has strong merits, the challenges for wide application in the short term are formidable since in the short to medium term, REDD+ will need to embrace a broad set of policies such as:

- Institutional reforms to improve governance, clarify tenure, decentralize appropriately and encourage community forest management.
- Changes in agricultural policy which could curb demand for new agricultural land and clearing of forests.
- Energy policies which could reduce forest degradation caused by harvesting wood fuel, while encouraging reduced-impact logging practices could lessen the harmful effects of timber extraction.

- Setting up protected areas could also be effective in conserving forests.

4.5 References

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5 Climate Change Policies: Cap and Trade

5.1 Cap-and-trade policies

Carbon markets mechanisms, or Emissions Trading Schemes (ETSs), are becoming an increasingly popular policy instrument to address climate change at the international and domestic levels. Increasing interest in ETSs is based on both political acceptability, due to the flexibility in their design, and the economic efficiency derived from allocating abatement effort to the lowest cost facilities. These attractive properties led to the introduction of ETSs initially at the national level – mainly in the United States – and later, following the positive evaluation of the existing schemes, at the regional level, the primary example being the European Union Emissions Trading System (EU ETS) for controlling GHGs. In the following sections, we briefly review the theoretical foundations of cap-and-trade policies, focusing on their efficiency properties; examine their main problems; and review selected applications, focusing mainly on those dealing with climate change.

5.1.1 The basic model

There are two types of tradable permit policies: credit systems and cap-and-trade systems. Credit systems work through the certification of credits to firms that reduce their emissions below the existing limits. The regulatory agency certifies the credits, which can then either be sold to other firms (that exceed their limits) or banked, to be used by the firm in subsequent periods. Under a cap-and-trade system, the regulatory authority first specifies the range of activities and the specific installations to be regulated, defines their total level of allowable emissions, assigns allowances to them (specifying the amount of emission per permit) and then distributes them (either free-of-charge or through an auction) to regulated installations. Allowances (permits) can subsequently be traded among installations. There are two types of initial permit distribution: free-of-charge (grandfathering), based on some predetermined framework such as historical emission levels; or selling the permits to firms through an auction. Although credit systems have been used, most applications are based on cap-and-trade systems, which are the focus of this section.

Under a cap-and-trade system, a quantity of allowances equal to the size of the cap is distributed by a regulatory body to the market, through grandfathering or by auction or through a combination of both. Subsequently, allowances can be bought and sold in a specified market. A firm holding a permit can release a quantity of pollutants (specified by the permit) into the environment. The total number of permits will be such that the emission target is achieved. Permits are the currency of a cap-and-trade program. Firms need to ensure that they have sufficient allowances to submit at every compliance period. Thus, those who emit more buy permits and those with lower emissions sell permits.

To illustrate the efficiency of a cap-and-trade system, we present a simple example. Assume that there are two firms, firm 1 and firm 2, emitting a harmful pollutant. Each firm can decrease its emissions by engaging in abatement activities. Figure 5.1 illustrates the two firms' marginal cost of abatement curves, $MAC_1(E_1^*)$ and $MAC_2(E_2)$, respectively, which increase as firms engage in higher levels of emissions reduction, that is,

$$\frac{\partial MAC_i(E_i)}{\partial E_i} < 0,\ i = 1,2$$

Firm 2 is assumed to be more efficient in abating emissions relative to firm 1. Since abatement is costly, in the absence of any regulation, firms 1 and 2 will not engage in

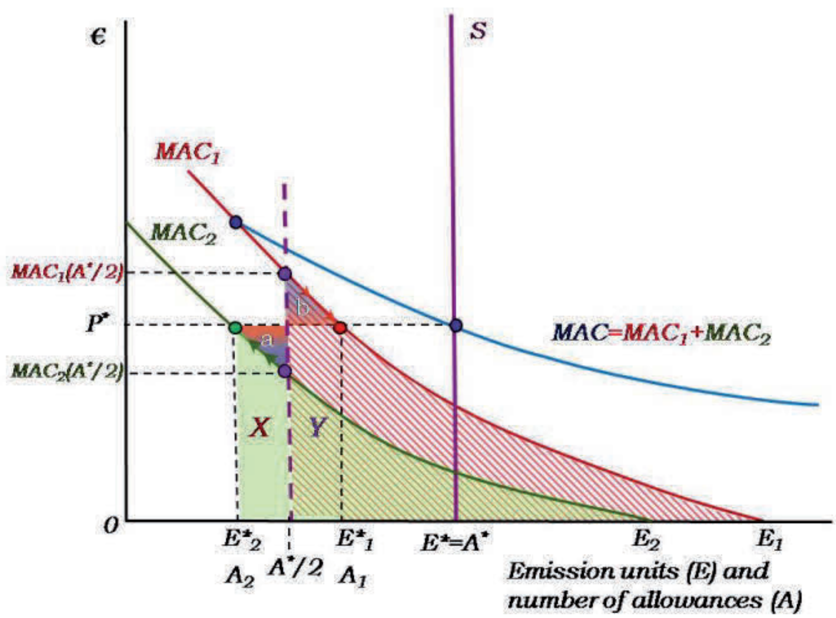

Figure 5.1. Competitive transferable emission permits market

abatement and their emission levels will be E_1 and E_2 respectively. The government decides to limit emissions to $E^* < E_1 + E_2$ and, in order to implement this goal, issues A^* number of permits.

The vertical line S in Figure 5.1 represents the total supply of permits. Assume first that the government auctions the permits. Firms can comply with environmental regulation by either controlling their emissions or purchasing permits. This means that their marginal abatement cost represents their opportunity cost of permits and thus MAC_i represents each firm's demand for permits, with the aggregate demand illustrated by the $MAC = MAC_1 + MAC_2$ curve (the horizontal sum of the individual MAC curves) in Figure 5.1. Assuming perfect competition, the permit price P^* will be determined at the intersection of the market demand for permits with the fixed supply of permits. Each firm will engage in abatement up to the point where the last unit of abatement costs the same as purchasing a permit. That is, firm i will emit E_i^* units of pollutant (abating $E_1 - E_i^*$ units) and will purchase A_i number of permits. At the equilibrium,

$$MAC_1(E_1^*) = MAC_2(E_2^*) = P^*,$$

thus securing the efficient allocation of permits.[15]

Alternatively, the government could distribute permits free-of-charge to the firms which are then free to trade permits in a competitive market. Assume that the government chooses a proportional allocation, with each firm receiving $A^* / 2$ permits. At the initial permit distribution, firm 1 has a higher MAC, that is, $MAC_1(A^* / 2) > MAC_2(A^* / 2)$. Firm 2 has an incentive to reduce its emissions further in order to free up some of its initial permits endowment and sell them to firm 1. Similarly, firm 1 has an incentive to purchase permits from firm 2, in order to be able to increase its emissions and reduce its abatement cost. This process will stop when the two firms' *MAC*s are equalized. The competitive market equilibrium will result in $MAC_1(E_1^*) = MAC_2(E_2^*) = P^*$, securing again the efficient allocation of permits. Notice that the final equilibrium does not depend on the initial distribution of permits; regardless of the initial starting point, trading opportunities will be exhausted only when the two firms' marginal abatement costs are equalized.

Allowing trading of emission permits reduces the cost of achieving a certain

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15 The government is trying to minimize the sum of environmental damages and the costs of abatement. That is, $\min TSC = D\left(\sum_{i=1}^{2} E_i\right) + \sum_{i=1}^{2} TCA_i(E_i)$, where TSC is the total social cost. The first-order conditions require that $\frac{\partial TSC}{\partial E_i} = 0 \Rightarrow MD = MAC_i$, that is, the efficient solution requires equalization of firms' marginal cost of abatement.

environmental target, in the above example limiting emissions to E^*, relative to the case in which permits were not tradable (which corresponds to a command-and-control type of policy). In reducing its need for permits by $A^*/2 - A_2$, firm 2 increases its abatement cost by the area X, while the purchase of an equal amount of permits allows firm 1 to decrease its abatement cost by the area Y (Figure 5.1). Since, by simple geometry, $Y > X$, it is clear that permits trading reduces the cost of achieving the environmental target.

The intuition behind this result is rather simple. Assuming a perfectly competitive market, permits will flow toward the firm that values them more, that is, the firm with the higher demand for permits, i.e., the higher MAC. Firm 2, the seller of permits, has a higher benefit from the sale rather than the own use of permits (at equilibrium, firm 2's total net benefits are denoted by the area a in Figure 5.1) and firm 1, the buyer of permits, gets more value from the permit it purchases than the price it pays for it (firm 1's total net benefits are denoted by the area b in Figure 5.1). Since both firms benefit from trading permits, the optimal amount of permits will be traded and efficiency will be achieved. The cost savings that a permit market achieves relative to conventional command-and-control regulations are higher, the more the cost of abating pollution differs among firms.

From the above discussion, it is clear that trading permits achieves 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 intuition is the same as above: trading of permits allows them to ultimately flow to their highest valued uses. Since those uses do not depend on the initial allocation, all initial allocations result in the same outcome and that outcome is cost effective. Therefore, the initial allocation can be used to serve other goals (such as political feasibility or ethical concerns) without sacrificing efficiency. This property of ETSs is quite important in regional and international agreements to combat climate change, since it allows the allocation of differential goals among countries without sacrificing efficiency, and will be discussed in greater depth later on.

5.1.2 Potential efficiency-reducing and design issues

The above-stated properties of ETSs hold under perfect conditions. Tradable permits systems may not achieve overall efficiency if market conditions are not present. The most important failures are the presence of market power and transaction costs. Because ETSs define an aggregate limit on emissions, which – assuming perfect monitoring and enforcement – cannot be violated, the consequences of these market imperfections affect mainly cost efficiency rather than environmental quality.[16] Furthermore, even in the presence of these imperfections, ETSs can be designed to mitigate their effects. We will briefly present the effect of these two market imperfections on the working of an ETS, keeping in mind that since emissions are capped, permits are a costly input.

Market power

In the presence of market power, there are two main ways in which an ETS could be the source of anti-competitive effects. First, a large participant in the permit market might exercise market power to manipulate the permit prices to increase revenue or decrease cost in the permit market. That is, a net seller will hold back unused permits to force a high permit price, while a large net buyer will demand fewer permits to keep the price low. Second, a firm might attempt to use its power in the permit market to increase its share and profits in the output market by purchasing more permits in order to force a high price, thus increasing its competitors' production costs, or – in the extreme case – to force competitors out of the product market.

Assuming no interaction between the permit and the output market, Hahn (1984) shows that a dominant firm will use its market power to inflate the permit price if it acts as a net seller of permits, and to depress it if it acts as a net buyer. In such cases, a permit market does not allocate permits efficiently, since

$$MAC_d(e_d^*) \lesseqgtr P^E = MAC_i(e_i^*),$$

where subscript d denotes the dominant firm and subscript i denotes the firms that take the price as given. Hahn suggests that, in order to restore the efficient solution, the regulator should provide the dominant firm with the exact number of permits it will in fact demand, thereby effectively removing it from the market and restoring competition.

Since permit costs influence product markets and firms are overall profit maximizers (they do not just care to minimize their cost of compliance with the environmental regulation), a firm with power in the permit market will choose the permit price taking into account total profits. Misiolek and Elder (1989) show that a dominant firm in both the permit and output markets will manipulate its demand for

16 Other potential problems that require careful design of the ETS include the temporal and geographical concentration of emissions that could result from banking and borrowing and from locational characteristics of the sources respectively. We do not consider these issues since they do not pose significant problems in the case of climate change.

permits so as to increase its market share and overall profits relative to the fringe. Similarly, Sartzetakis (1997a) shows that a dominant firm may use emission permits to increase its market share and profits in the product market. Fershtman and Zeeuw (1996) and Van Long and Soubeyran (1997) point out the possibility that trading of emission permits may facilitate cooperation among oligopolists by allowing credible commitments that bypass antitrust regulation.

Furthermore, a firm with power in both the permit and the product markets, which receives a substantial amount of permits free-of-charge, might manipulate prices in both markets so as to increase its profits, not primarily at the expense of its rivals but rather at the expense of consumers and taxpayers. This possibility has received considerable attention during the first two phases of the EU ETS and has been termed **windfall profits**, that is, profits resulting from free allocation of permits (see for example Neuhoff et al., 2006, Sijm et al., 2006, Ellerman and Joskow, 2008). Disegni Eshel (2005) and Hintermann (2011, 2017) show that a dominant firm could increase the permit price even when it is a net permit buyer, as long as the increase in its revenue in the output market plus the increased rents from the free allocation of permits exceed the increased compliance costs.

Sartzetakis (1997b, 2004) shows that if the product market is oligopolistic, efficiency is not achieved even in the case of perfectly competitive permit markets. This is because firms that are less efficient in abatement, at the equilibrium use more permits and abate less relative to the more efficient firms (which leads to a decrease in overall abatement cost and achieves efficiency if the product market is competitive) and thus the less efficient firms decrease their overall marginal cost and become more aggressive in the output market, acquiring in return more permits. As a result, the less efficient firms end up with a share of emission permits that is higher than the welfare maximizing share. If the firms that are less efficient in abatement are also less efficient in production, competitive trading of permits may result in lower output and welfare. Therefore, the property of competitive permit markets that ensures that permits flow to their highest valued uses drives efficiency under perfectly competitive product markets, but could distort efficiency if product markets are non-competitive.

Transaction costs

Transaction costs consist of administrative and trading costs which could influence the permit market. They are incurred at several stages: first, at the stage in which firms prepare their administrative systems to comply with the requirements of the regulation; second, at the stage of trading, including search, information, bargaining and decision-making costs; and finally, at the reporting stage, including application, registry accounts, monitoring, reporting and verification costs. These costs could either be proportional to the number of permits traded (trading costs), creating a spread between the purchase price and the net amount the seller receives, or they might not depend on the volume of transactions (fixed administrative costs), in which case they might influence participation in the permit market.

Assuming first that transaction costs are proportional to the number of permits traded, a spread between the purchase price and the net amount the seller receives is created. To simplify the presentation, assume that the permit price, P^E, includes the transaction costs incurred by the buyer of permits, and selling permits bears an additional cost at a rate t.[17] Therefore, cost efficiency of the permit market is again violated, since

$$MAC_{buyer} = P^E > P^E - t = MAC_{seller}.$$

This price gap creates an incentive to hold permits that would have been sold, had the market been frictionless. In the case of permit grandfathering, a firm may decide to use some permits that it would never buy at market price, clearly distorting the market outcome. Due to transactions costs, a firm possessing permits has lower marginal cost than a competitor who needs to buy them ($MAC_{seller} < MAC_{buyer}$).

Second, the presence of fixed administrative transactions costs, even in the absence of variable costs, could also yield similar results. For example, if the fixed administrative costs are considered extremely high by a relatively small firm, this firm might choose not to participate in the permit market: for such firms, using permits has no opportunity cost. This implies that in the case of permit grandfathering, giving small amounts of permits to many small firms may result in output increases, while giving large amounts to some large firms works as a lump sum transfer (Constantatos et al., 2014).

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. Furthermore, Stavins shows that, in the presence of transaction costs, the initial distribution of permits affects permit-trading decisions. Cason and Gangadharan (2003) confirm these results in an experimental setting. Montero (1998) incorporates uncertainty in the model with transaction costs and

17 It is clear that the spread of transaction costs between the seller and the buyer influences only their net benefits. As long as there is a gap between the price the buyer pays and the price the seller receives, the efficiency property does not hold.

examines their effect on the permit market's performance and control costs.

While the above-mentioned literature examines the impact that transaction costs have on the efficiency of permit markets, Constantatos et al. (2014) examine the effect of transaction costs in an international permit market (such as the EU ETS), by considering the possibility that governments could use permits strategically. In particular, they show that in the presence of fixed and/or per-unit transaction costs, permits grandfathering affects output decisions, and so it can be used for strategic trade purposes, thus distorting international competitiveness. If participation in the permit market entails fixed costs, some firms may choose to stay out of the permit market, complying with the regulatory requirements by abating and using any amount of grandfathered permits they receive. Clearly, in this case the amount of grandfathered permits affects production choices. On the other hand, variable transaction costs drive a wedge between buyers' and sellers' opportunity cost of using permits in the production process. Grandfathering a number of permits to a firm is equivalent to offering that firm a unit cost reduction.

5.1.3 Review of past, present, emerging and potential Emissions Trading Schemes

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

When first introduced as an alternative to the command-and-control mechanisms, ETSs were quite controversial and received strong criticism on ethical and practical grounds. On ethical grounds, many believed that issuing allowances legitimized environmental degradation, while there was wide disbelief regarding the workability of such policies. The success of the early *netting* and *bubbles* programs that allowed trade of emissions reductions among installations within the firm in the late 1970s and early 1980s in the United States (Tietenberg, 1985, Hahn, 1989), and later the *offset* programs that allowed trading among firms, convinced regulators of the workability and the significant compliance cost savings of permit trading. Furthermore, more careful definition of permits as allowances rather than rights, along with continuous discussions, removed most of the environmental community's hesitation about ETSs.

Early applications

The above-mentioned *netting*, *bubbles* and *offset* programs were followed by continuously more ambitious programs, such as the lead trading program that allowed flexibility and reduced cost in phasing down lead from gasoline in the United States (Hahn, 1989); the SO_2 allowance trading system that regulated SO_2 emitted by electric power generating units in the US and generated very high cost savings (Carlson et al., 2000); and a number of other regional and state-level trading programs in the US, regulating NOx and SO_2 emissions (RECLAIM program) and VOC (volatile organic compounds) emissions. Apart from regulating emissions, trading programs were used at the state level in the US in order to control effluent charges. The U.S. Environmental Protection Agency (2001) reported on numerous state-level effluent trading programs in various stages of development.

Outside of the United States, in the early stages there were two Canadian pilot programs initiated in the late 1990s: the Pilot Emission Reduction Trading and the Greenhouse Gas Emission Reduction Trading projects, which did not yield substantial trading. Other early, but less substantial, programs include the CFC (chlorofluorocarbon) trading in the initial phase of the Montreal Protocol that allowed a firm to produce a given amount of CFCs if it had an allowance to do so (Hahn and McGartland, 1989), the tradable permit system for total suspended particulates from stationary sources in Santiago, Chile (Montero and Sfinchez, 1999) and the UK's trading program that allowed intra-firm trading of SO_2 allowances among large combustion plants (Sorrell, 1999).

A survey in 2000 found nine applications in air pollution control, 75 applications in fisheries, three applications in managing water resources, five applications in controlling water pollution and five applications in land use control (OECD, 2000, Appendix 1). Following the publication of the OECD survey, there have been many more applications of ETSs at the regional, national and sub-national level.

In the following sections, we review the more recent developments, focusing on the three most important existing programs, which are: the EU ETS established in 2005 by the European Union; California's Cap-and-Trade System enacted in 2006; and the Regional Greenhouse Gas Initiative (RGGI), established in 2009 by nine northeastern states in the United States.

The European Union Emissions Trading System

The EU ETS is the largest cap-and-trade program in terms of the countries participating (the 28 EU Member States, plus Iceland, Liechtenstein and Norway), the emissions covered (CO_2 emissions; nitrous oxide emissions from all nitric, adipic, glyoxylic acid and glyoxal production; and perfluorocarbons emissions from aluminium production), and the sources under obligation. It caps the volume of GHG emissions from installations and aircraft operators responsible for around 45 percent of EU GHG emissions, covering approximately 11,000 stationary installations in the electric and major industrial sectors and, as of 2014, all domestic airline emissions (approximately 520 airlines flying between European airports). The cap-and-trade program was selected as the policy instrument to meet the EU's Kyoto commitments. The first design of the EU ETS was presented in the "Green paper on greenhouse gas emissions trading within the European Union" (Unspecified, 2000) which led, through stakeholder consultation, to the adoption of the EU ETS Directive in 2003 and the introduction of the EU ETS in 2005.

The program is currently in its third phase and has evolved significantly from its initial design (Ellerman et al., 2016). The first phase of the EU ETS ran from 2005 to 2007 and was mainly a pilot phase during which the necessary infrastructure for emissions monitoring, reporting and verification was established. The second phase ran from 2008 to 2012 and established the effective functioning of the market. During the first phase, participating installations were allowed to use units generated under the Clean Development Mechanism (CDM), as specified in the Kyoto Protocol, to meet their EU ETS obligations, while during the second phase they could also use emission reduction units generated under joint implementation (JI).[18] During the first two phases, initial allocations of allowances were mostly free-of-charge. The third phase runs from 2013 to 2020 and includes many changes which were made based on lessons learned from the previous two phases. The third phase of the program is not the final one, since it is foreseen that the EU ETS will continue on to phase four starting in 2021.

The program's main design elements during the currently-running third phase are: moving gradually from grandfathering to auctioning as the main allocation method, starting the phasedown with electric utilities; moving from national registries to the EU registry; adopting a single EU-wide cap, decreasing each year by a linear reduction factor of 1.74 percent relative to the average total quantity of allowances issued annually in 2008-2012; and changes in the offsets that limit their use. Although auctioning is the default method for allocating emission allowances to installations during the third phase, some grandfathering of allowances will continue.

18 Under the Kyoto Protocol, CDM projects generate Certified Emission Reductions credits while JI projects generate Emission Reduction Units credits. Each credit is equivalent to 1 ton of CO_2.

The main purpose for continuing grandfathering of allowances is to address the issue of carbon leakage (i.e., installations moving to third countries with lower or no regulatory restrictions because of increased costs related to ETSs). Grandfathered allowances will reward efficient installations and also accommodate new entrants. Electricity production no longer receives any free allowances.

The single EU registry tracks the ownership of allowances and the transactions concerning allowances, similar to a bank, recording the amounts owned on its accounts and the transactions between accounts. This single registry is operated and maintained by the Commission, whereas national registry administrators in all 31 countries participating in the EU ETS remain the point-of-contact for the representatives of more than 20,000 accounts (companies or physical persons) (European Commission, 2017b).

The annual emission cap (excluding aviation) was set at 2,084.3 MtCO_2eq, declining by a factor of 1.74 percent annually, thus reaching 1,931.2 MtCO_2eq in 2017 and expected to reach 1,816.5 MtCO_2eq in 2020. Figure 5.2 illustrates the emission caps during the three phases of the program, including aviation allowances (European Commission, 2015). Finally, although Certified Emission Reductions (CERs) and Emission Reduction Units (ERUs) credits are still admitted in the third phase, stronger rules apply, which include higher quality standards, exclusion of nuclear and afforestation and reforestation projects, and admission of credits from new projects registered after 2013 only in least developed countries. After 2020, the European Council has decided not to admit international credits anymore.

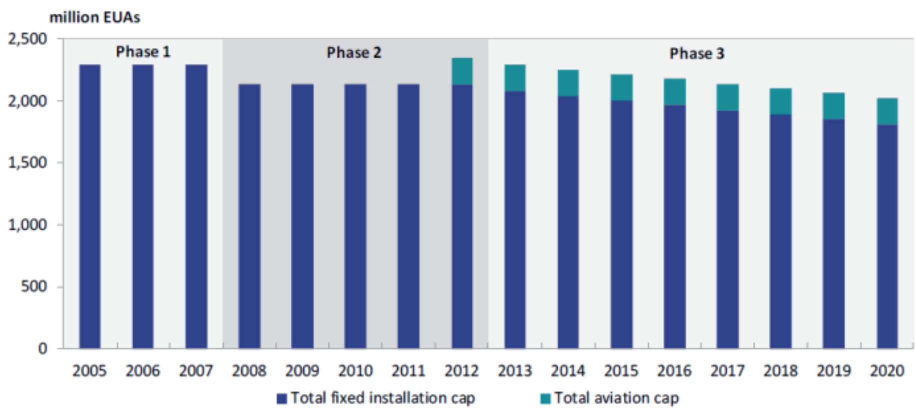

Figure 5.2. Emission caps during the three phases of the EU ETS

Source: European Commission, 2015, *EU ETS Handbook,* Climate Action Publications, p. 22.

Emissions from stationary sources decreased from 2,375 to 1,813 $MtCO_2eq$ between 2005 and 2014, which amounts to a 24 percent decrease. Compared to the cap for 2020, which as mentioned above is 1,816 $MtCO_2eq$, it is quite surprising that this target was already reached in 2014. Despite this significant decrease in emissions during the EU ETS's implementation, there is controversy as to whether this decrease is due to the program or to the economic crisis (Gloaguen and Alberola, 2013). However, there is evidence that the EU ETS has spurred investment in abatement across member states (Arlinghaus, 2015).

The prices in the EU ETS are presented in Figure 5.3. The price of permits exhibited high volatility, starting below €25 in 2005, peaking at about €30 by early 2006, then dropping below €10 and crashing to a record low of €2.81 in 2013, with

Figure 5.3. Price trends for European Union allowances and CERS

Notes: CERs: certified emission reductions. The EUA price represents historical spot price data from the secondary market in the first and second trading periods. In the third trading period, the EUA price refers to auctioning data from the EEX and ICE trading platforms. The CER price up until the middle of 2014 is based on historical spot price data from Point Carbon. The more recent data up until the end of 2015 are based on future CER prices from the ICE trading platform. The break in the EUA price between 2007 and 2008 reflects the lack of banking provisions between the first and second trading periods. However, trade in future EUA contracts did take place during this period at a higher level.

Source: European Environment Agency (2017), "Trends and projections in the EU ETS in 2017 The EU Emissions Trading System in numbers", European Environment Agency, Copenhagen, Denmark, Figure 2.5. © European Environment Agency, 2017.

the price varying between €4 and €7 during 2015-2016. Since banking of allowances was not permitted between the first and the second phases, the price remained close to zero until mid-2008.

The prices in the EU ETS, along with the supply of allowances, verified emissions and cumulative surpluses, are presented in Figure 5.4. Given that the cap in the second phase was more stringent and verified emissions exceeded the supply of allowances in 2008, the spot price of allowances in the secondary market reached €25 in 2008 (Figure 5.3). In the following years, as shown in Figure 5.4, the supply of allowances exceeded verified emissions until 2013. This surplus pushed down allowance prices which settled around €7 by the end of the second phase. As shown in Figure 5.4, the spot price of auctioned allowances during the third trading period fluctuated between €4 and €7.

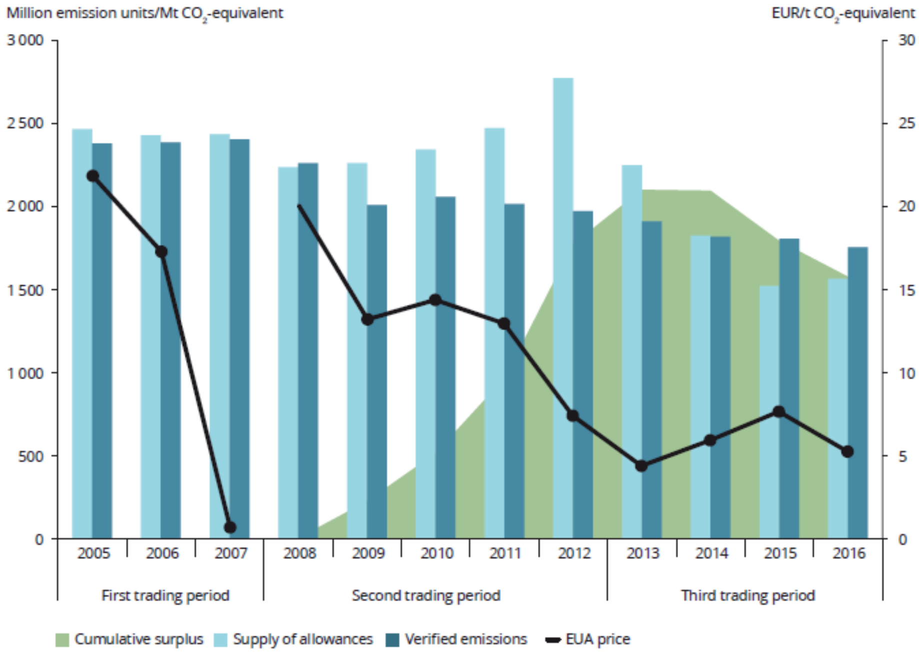

Figure 5.4. Emissions, allowances, surplus and prices in the EU ETS, 2005-2016

Notes:

- EUA: EU allowance (1tCO_2eq). Verified emissions and allocations shown in this figure for the years before 2013 were adjusted by the EEA to be comparable with those from the third trading period of the EU ETS (2013-2020).
- The supply of allowances presented takes into account a redistribution, by the EEA, of annual

volumes of allowances auctioned/sold on the primary market, from the year when they were released to the market to the years from which they arise. For example, the volumes of allowances relative to the second trading period (2008-2012) but sold/auctioned in the first months of 2013 are added here to the 2012 figures.

- The average EUA price represents historical spot price data from the secondary market in the first and second trading periods. In 2008, only EUA spot prices for the second trading period are considered in the calculation of the average. In the third trading period, the EUA price refers to primary market auctioning clearing prices from the trading platforms EEX and ICE.
- The break in the EUA price between 2007 and 2008 reflects the absence of banking provisions between the first (2005-2007) and second (2008-2012) trading periods. However, trade in future EUA contracts did take place during this period.
- The cumulative surplus represents the difference between allowances allocated for free, auctioned or sold plus international credits surrendered or exchanged from 2008 to date minus the cumulated emissions. It also accounts for net demand from aviation during the same time period.

Source: European Environment Agency (2017), "Trends and projections in the EU ETS in 2017 The EU Emissions Trading System in numbers", European Environment Agency, Copenhagen, Denmark, figure ES.1. © European Environment Agency, 2017.

The volume of trades showed a considerable increase over the years 2005-2013, reached its peak in 2013, and dropped in 2014 and 2015. Figure 5.5 presents the EU ETS trading volume for the eleven-year period from 2005 to 2015.

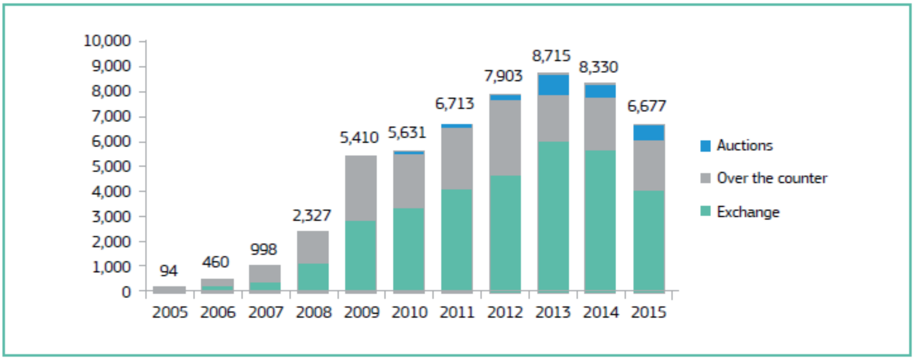

Figure 5.5. Trading volumes in EU emission allowances (in millions of tons)

Source: European Commission, 2016, "The EU Emissions Trading System (EU ETS)", Factsheet, available at https://ec.europa.eu/clima/sites/clima/files/factsheet_ets_en.pdf. © European Union, 2016.

Despite the low prices in recent years, permit auctions have been generating significant revenues for the participating countries. During the four-year period 2012-2016, around three billion allowances were auctioned, with total revenues from auctions accruing to the participating Member States exceeding €7 billion (European

Environment Agency, 2017). For example, during the third trading period, revenues from auctioning for Germany reached approximately €3.5 billion, €1.8 for the UK, €1.7 for Italy and €0.6 billion for Greece (see Figure 5.6). Of this amount, around 80 percent has been used, or is planned to be used, for climate and energy purposes (European Commission, 2017a).

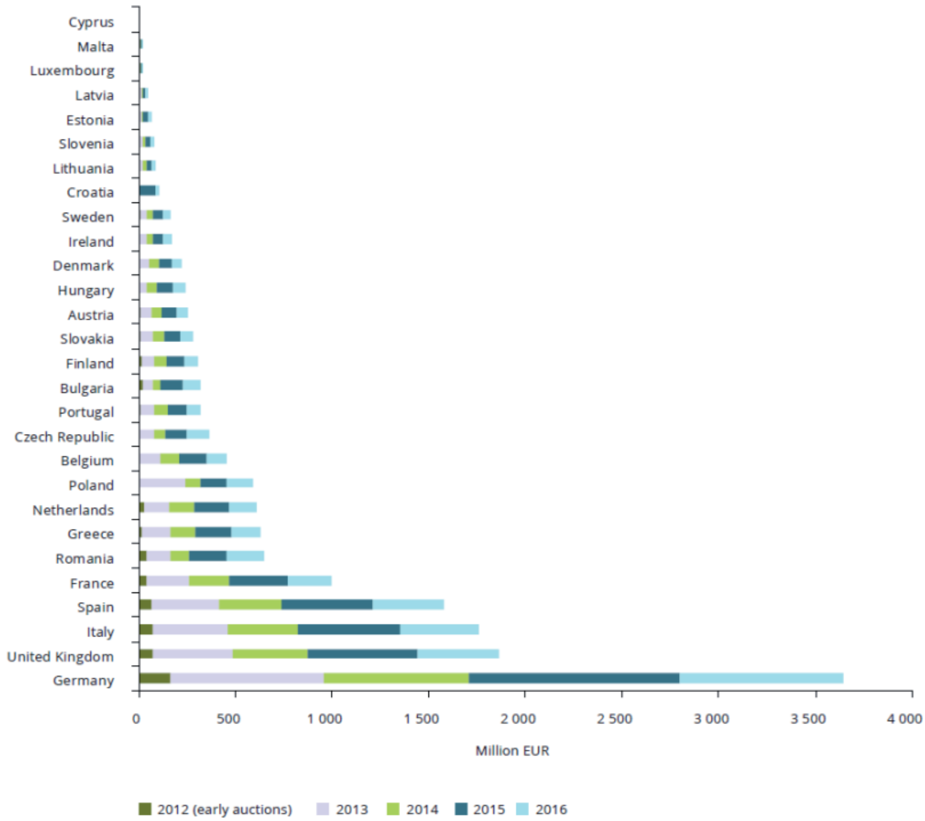

Figure 5.6. European Union allowances (EUAs) auction revenues, by member state, in the third trading period

Notes: 2012 (early auctions) refers to amounts that pertain to the year 2013, but were already auctioned a year earlier.

Source: European Environment Agency (2017), "Trends and projections in the EU ETS in 2017 The EU Emissions Trading System in numbers", European Environment Agency, Copenhagen, Denmark, figure 2.6. © European Environment Agency.

One important problem that has been identified is the creation of a substantial allowances surplus. As shown in Figure 5.4, the surplus was around 2 billion allowances at the start of the third phase, increased to more than 2.1 billion allowances in 2013, and then dropped to around 1.7 billion allowances in 2016 as a consequence of **back-loading**, that is, the initial decision of the Commission to postpone the auctioning of 900 million allowances until 2019-2020. More interesting is the long-run remedy to the problem, required to stabilize allowance price. 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 shocks (such as economic recessions). Furthermore, the back-loaded allowances in 2014-2016 will be transferred to the reserve, rather than auctioned in 2019-2020.

Two recent applications in the United States

California's Cap-and-Trade program (CaT) is part of the state's policy to reduce GHG emissions to their 1990 levels by 2020. The program covers about 450 installations in a variety of sectors (similar to those covered by the EU ETS). The first phase started in January 2013 and initially included electricity generators and importers and large industrial facilities, while it has been expanded since 2015 to include distributors of transportation, natural gas and other fuels. In its second phase which started in 2015, it covers almost 85 percent of California's GHG emissions. Its main design elements are allowances which are allocated mostly free-of-charge, while auctioning a small part with the intention of gradually increasing the number of allowances auctioned; and an overall cap that declines about 3 percent, starting from 2015 to 2020. The system was linked to a very similar system in Quebec in 2014. The program has held 14 quarterly auctions (the last six of which were joint auctions with Quebec) in which the permit price has ranged from $10.09 (November 2012) to $12.73 (February 2016), generating about $3.5 billion in revenues. Although the CaT program exhibits stability and emissions show a decline, similar to the EU ETS, it is debatable whether this decline can be attributed to the program alone.

The RGGI, established in 2009 by nine northeastern states,[19] was the first cap-and-trade program in the United States aimed at reducing CO_2 emissions. The program covers CO_2 emissions from power plants that exceed a certain capacity and are located within the states participating in the RGGI; these plants numbered 211 in the first phase and currently, following New Jersey's withdrawal, total 168 facilities. RGGI's main design elements are: the cap was set in 2014 at 91 million short tons[20]

19 Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New York, Rhode Island and Vermont currently participate in the program. New Jersey withdrew at the end of 2011.
20 Short tons can be converted to metric tons by multiplying the number of short tons by 0.907184.

of CO_2 and declines 2.5 percent each year from 2015 to 2020[21]; most of the allowances are auctioned (90 percent) and banking is allowed. An interesting characteristic of the program is that it effectively sets price ceilings and floors. The price ceilings are exercised by releasing reserves allowances in the market when auction prices reach certain high levels, while the price floors are exercised by setting auction reserve prices. The program held 36 auctions up to 2017, with the price at the last auction settling at $2.53.[22] The program has generated over $2.7 billion in revenues since its inception, most of which has been invested in programs including energy efficiency, clean and renewable energy and GHG abatement (RGGI, 2016).

Additional recent applications and planned ETSs

Besides the three emissions trading programs discussed above, there are other national or sub-national systems already operating or under development in Canada, China, Japan, New Zealand, South Korea and Switzerland. China has been involved since 2014 in the design and implementation of emissions trading, a program which is supported by the European Commission through the provision of technical assistance for capacity building. This very ambitious program supports the seven regional pilot systems already set up and the establishment of a nationwide emissions trading system. In 2015, Korea launched an emissions trading system (KETS) that covers around 66 percent of Korea's total GHG emissions. It is the first mandatory ETS among non-Annex I countries under the UNFCCC and is supported by the European Commission through the provision of capacity building assistance. The KETS could trigger the expansion of emissions trading among emerging economies and developing countries.

By 2016, about 40 national jurisdictions and over 20 cities, states, and regions had put a price on carbon, either through taxes or through the use of ETSs, as illustrated in Figure 5.7. This translates into a total coverage of around 7 gigatons of carbon dioxide equivalent ($GtCO_2eq$) or about 13 percent of global GHG emissions, approximately 9 percent covered by ETSs and 4 percent by carbon taxes. Pricing of these instruments ranges between $1 and $130/$tCO_2eq$, with 85 percent of the emissions being priced under $10/$tCO_2eq$. These instruments generate proceeds just below $50 billion per year (World Bank Ecofys and Vivid Economics, 2016).

21 From 2009 to 2011, the cap was 188 million short tons per year for the ten-state region. From 2012 to 2013, the cap was 165 million short tons per year for the nine-state region.
22 The price has varied from $1.86 (Auctions 9 and 10 in 2010) to $7.50 (Auction 30 in 2015).

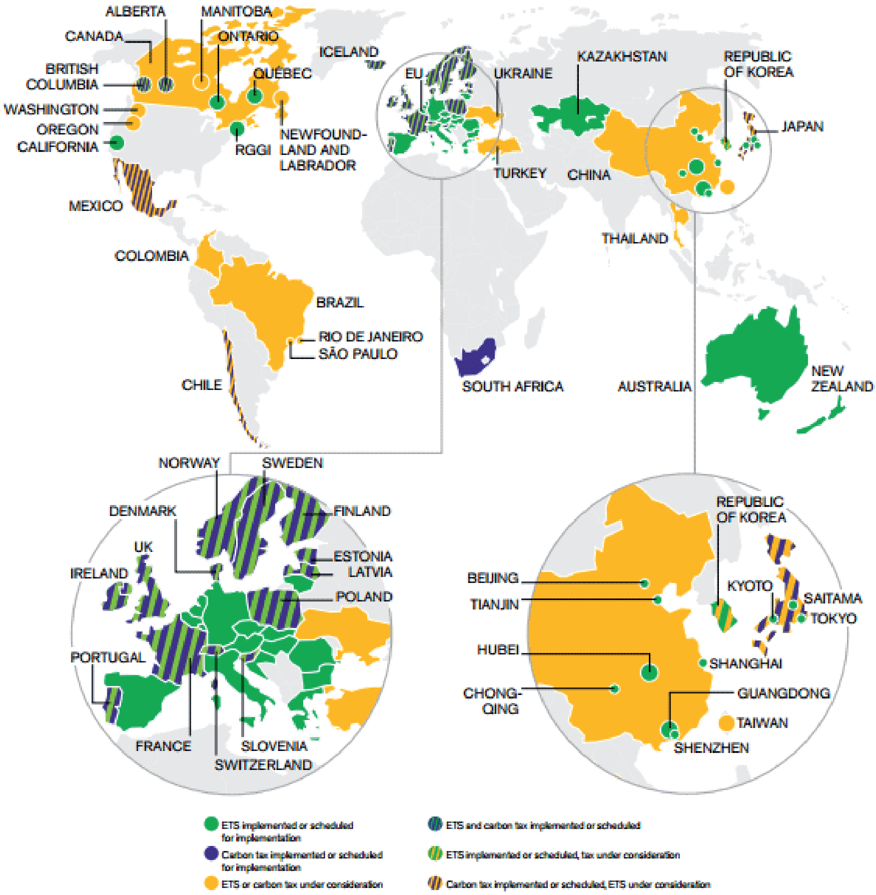

Figure 5.7. Summary map of existing, emerging and potential regional, national and subnational carbon pricing initiatives (ETS and tax)

Source: World Bank, Ecofys and Vivid Economics, 2016, *State and Trends of Carbon Pricing 2016* (October), World Bank, Washington, DC, Doi: 10.1596/978-1-4648-1001-5. License: Creative Commons Attribution CC BY 3.0 IGO.

5.1.4 Evaluation of Emissions Trading Schemes and lessons for the future

Contrary to theoretical expectations, the experience of cap-and-trade systems up to now provides mixed results as to their effectiveness in curbing emissions while their cost efficiency is less debatable. For California's Cap-and-Trade program and the RGGI program, there is not sufficient data for detailed analyses, but all studies show that they are moving in the right direction. While the EU ETS has received a lot of praise and acknowledgement for achieving emission reductions in a cost effective way, it has also received significant criticism focused mainly on the issues of windfall profits and over-allocation. The former refers to the increased prices of electricity which resulted in higher corporate profits, mainly due to the free allocation of allowances, and the latter refers to the fact that the emissions cap was not sufficiently stringent. Although passing the cost of allowances on to electricity prices was expected, the extent of the price increase cannot be explained given the supply of permits, which has given rise to a discussion regarding distortions due to market power (Hintermann, 2014). It is expected that moving to increasingly more demanding caps and to auctioning of allowances will correct these issues.

Although there is no evidence of market power distortions in the existing ETSs, apart from the above-mentioned instance, there is considerable evidence of distortions due to transaction costs. Rose (1994) suggests the existence of transaction costs in the SO_2 permits program, Kerr and Mare (1998) estimate efficiency losses from the presence of transaction costs in the lead permits program and Gangadharan (2000) shows that transaction costs were significant in the RECLAIM program, influencing the choice of participation in the market. Jaraite et al. (2010), using data from Irish firms participating in the EU ETS, find that transaction costs are significant, particularly for smaller firms at the early stages of the program. Heindl (2012), using data from two surveys of German firms participating in the EU ETS, reports significant transaction costs, which result in welfare losses. Furthermore, it is shown that transaction costs are relatively higher among smaller firms. Jaraite and Kazukauskas (2012), using data from all countries participating in the EU ETS, report significant transaction costs that influence firms' behavior in the permit market. They also show that small firms were less likely to participate in the market and a number of them did not sell their surplus allowances. Finally, Hahn and Stavins (2011) review and evaluate empirical evidence of potential violation of cost-effectiveness and neutrality of the permits' allocation due to a number of conditions including transaction costs, in eight cap-and-trade programs. They find that in some programs cost-effectiveness and neutrality hold strong, while in some others these properties are absent due to distortions, among which the most prevalent is the presence of transaction costs. One remedy for reducing transaction costs is to increase the size of the permit market. Average administrative costs will decrease as the market size increases, due to economies of scale.

Table 5.1. Major cap-and-trade applications

System	Geographic scope	Coverage & sectors	Time period	Allowance allocation method	Cost containment mechanisms	Environmental and economic performance
Regional Clean Air Incentives Market (RECLAIM)	South Coast Air Quality Management District, CA	NOx & SO2 from electric power & industrial sources	1993-present	Free	--	Emissions lower than with parallel regulations; unquantified cost savings; electricity crisis caused allowance price spike and temporary suspension of market
NOX Trading in the Eastern United States	12-21 U.S. States	NOx from electric power & industrial sources	1999-2008	Free	--	Significant price volatility in first year; NOx emissions declined from 1.9 (1990) to 0.5 million tons (2006); cost savings 40-47 percent
Regional Greenhouse Gas Initiative	Nine northeastern U.S. States	CO2 from electric power	2009-present	Nearly 100% auction	banking, cost containment reserve, auction reservation price	Cap non-binding then barely binding due to low natural gas prices; has generated more than $1 billion for participating states
AB-32 Cap-and-Trade	California, USA	CO2 from electric power, industrial, & fuels	2013-2020	Transitions from free to auction	banking, allowance price containment reserve, auction reservation price	Covers 85% of emissions; reduces competitiveness effects w/output-based updating (OBU) allocation; linked with Quebec cap-and-trade system
European Union Emissions Trading System	27 EU Member States plus Iceland, Lichtenstein, & Norway	CO2 from electric power, large industrial, & aviation	2005-2020	Transitions from free to increased use of auctions	limited banking, previous use of offsets from CDM	Over-allocation by member states in pilot phase; suppressed allowance prices due to "complementary policies," CDM glut, slow economic recovery
New South Wales, Greenhouse Gas Reduction Scheme	Australia	CO2/Carbon Transferable NSW Greenhouse Abatement Certificates	2003-2012	Tradeable credits could be earned by all generators for attaining intensity below annual average	--	Efficient abatement, high compliance at low cost. Improved methodologies in measuring and verifying emissions. Effects were moderated by a rising emissions intensity baseline
Carbon Reduction Commitment Energy Efficiency Scheme	United Kingdom	CO2/Carbon Allowance trading system	2008-present	Allowances are allocated at a fixed price	--	Possible overlap with the EU trading system

Source: Adapted from Schmalensee and Stavins, 2015.

Schmalensee and Stavins (2015) review the seven most prominent ETSs, which in their opinion are: the U.S. Environmental Protection Agency's leaded gasoline phasedown in the 1980s; the sulfur dioxide allowance trading program under the Clean Air Act Amendments of 1990; the Regional Clean Air Incentives Market in southern California; NOx trading in the eastern United States; the Regional Greenhouse Gas Initiative in the northeastern United States; California's AB-32 cap-and-trade system; and the European Union Emissions Trading System. Table 5.1 provides a brief overview of some of these systems, along with two systems in Australia and the UK, and the evaluation of their environmental and economic performance.

The experience from implementing cap-and-trade programs yields significant lessons for their improvement. First, although allocating allowances free-of-charge can build political support, auctioning of permits has important benefits such as increasing the cost of price manipulation and – most importantly – generating significant public revenues. Thus, as markets mature and abatement technology improves, the transition from grandfathering to auctioning is both necessary and feasible. Second, in order to decrease the volatility of the price of allowances, it might be of interest to examine the practice of California's program that effectively establishes ceilings and floors to the price of permits (through the release of reserved allowances when price increases and the establishment of an auction reservation price). Finally, the wider the market coverage is, the less vulnerable the market will be to problems of market power and transaction costs.

As many different regional, national and sub-national markets develop around the globe, one way to increase market coverage is to link these different programs, an issue that has received attention in the last few years (Stavins, 2016). Linking compatible ETSs with each other, apart from decreasing the threat of market power and reducing transaction costs, has the potential to generate other benefits that include increasing market liquidity, stabilizing the price of allowances, improving international collaboration on climate change and harmonizing carbon prices across different jurisdictions (Bodansky et al., 2015). Efforts to link different programs can use the experience from linking California's system to a very similar system in Quebec. The EU and Switzerland signed an agreement in November 2017 to link their systems, which will allow participants in the EU ETS to use allowances from the Swiss system for compliance, and vice versa (European Commission, 2017c). Similar efforts were pursued to link the EU and Australia programs before the repeal of the Australian system in 2014.

5.1.5 Comparison of taxes vs permits

Environmental taxes and tradable emission permits are, in the absence of other distortions, theoretically equivalent in terms of achieving the optimal level of emissions at the lowest possible cost (Baumol and Oates, 1988, Xepapadeas, 1997). Taxes set the market price, which (if the tax is set correctly) by fixing marginal costs, results in the optimal quantity of pollution. Permits set the optimal quantity, which leads to the market price.

However, the equivalence breaks if there is uncertainty over benefits and costs. Since both instruments obtain the same level of emissions even when benefits are uncertain, the interesting case arises in the presence of cost uncertainty. In this case, a tax that fixes the marginal cost leads to an uncertain level of emissions, while an ETS that fixes the level of emissions results in an uncertain permit price (i.e., marginal cost). Weitzman (1974) shows that, under cost uncertainty, the efficiency of a tax relative to an ETS depends on the pattern of costs and benefits. In particular he concludes that taxes perform better when the marginal benefit curve is flatter relatively to marginal cost and tradable permits perform better when the marginal cost curve is relatively flat. Part of the significant literature that emerged identified different parameters that favor either instrument, while another part suggests that a combination of the two policies could perform better (McKibbin and Wilcoxen, 1997, Pizer, 1997). Such a system would be based on a permit system (with complete or partial grandfathering of permits) with a number of permits held in reserve to be made available when certain trigger prices are reached. A program similar to this type of proposed hybrid system has been adopted in the case of the RGGI program, as described earlier.

There is some debate over the long-run properties of the two policies, since under an ETS that grandfathers permits, the cost of permits for a firm that receives e_0 permits free-of-charge and emits e units is $P^E(e-e_0)$, while with a pure Pigouvian tax t, its cost is te. Baumol and Oates (1988) show that long-run efficiency is achieved by both such policies since free permits are not considered as subsidies but rather as property rights and thus do not affect exit-entry decisions. Other authors suggest that, in order to achieve long-run efficiency, an ETS should auction all permits, while others suggest using tax thresholds, that is, a level of uncharged emissions e_0, making the cost under tax $t(e-e_0)$. Pezzey (2003) provides a rigorous summary of different arguments regarding the long-run comparison of the two policy instruments and the institutional design required to develop a tax-with-thresholds-as-rights system. However, he concludes that there is no need to move to a single policy scheme, since a mixed system seems to perform better in terms of efficiency, applicability and acceptability.

An ETS has an additional disadvantage due to potential imperfections in the permit market. However, as we reviewed above, there are no reports of significant problems related to market distortions in the existing ETSs. With respect to transaction costs related to monitoring, reporting, and verification, those are present under both taxes and permit systems. Coria and Jaraite (2015), using data from Sweden that implemented a CO_2 tax in 1991 and participates in the EU ETS, provide empirical support to the claim that transaction costs from monitoring, reporting, and verification are larger under emissions trading than under carbon taxation.

Finally, there are some more practical issues such as the cost of administering each system, and also political issues. On the one hand, cap and trade is considered more politically acceptable since it is market-based and does not involve the 'T word' (tax). On the other hand, a tax covers the entire economy and provides a clear price and revenues. The debate regarding the choice of policy instruments continues, with many different arguments made for either side (the views of some prominent people were presented at YaleEnvironment360, 2009). It seems though that a hybrid system involving either tax threshold levels or permit price floors and ceilings could be a better performing choice.

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6 Adaptation to Climate Change

6.1 Introduction

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 out in the Paris Agreement, severe impacts will occur in the following century. For instance, recent studies show that the Arctic as we know it today is almost certainly gone and the ramifications to which we will have to adapt will be severe. This section provides an overview of the economics of adaptation and the material that will be covered in the sections that follow. The structure of the themes presented here is largely in line with most recent literature reviews on adaptation, which understandably have much in common. This chapter relies heavily on these reviews (e.g., Downing, 2012, Chambwera et al., 2014, Markandya et al., 2014, Massetti and Mendelsohn, 2015, Fankhauser and McDermott, 2016, Kahn, 2016, Fankhauser, 2017).

The next section, Section 6.2, provides a presentation of the broad outlines of the theory of adaptation economics, starting with the big picture of adaptation from the global perspective, where mitigation and adaptation must be decided in tandem, and then limiting the analysis to a country perspective that takes climate change as a given (once global action has been determined) and must decide how much to invest in adaptation. The theory of adaptation economics considers both the role of private or market adaptation and that of the public authorities (whether local communities, cities, nations or international bodies). Section 6.3 considers the various analytical and empirical methods that have been used by economists to study impacts of climate change and adaptation. These are broadly categorized as integrated assessment models, empirical analysis, economy-wide simulation and decision-making tools. Section 6.4 provides a brief overview of studies that have been undertaken to estimate the costs of adaptation at a global level and at a sectoral level. In addition, the sectoral analysis presents evidence of private adaptation as well as public adaptation policies. The final section, Section 6.5, presents the literature on climate adaptation policy instruments.

6.2 Theory of adaptation economics

6.2.1 Introduction to adaptation

This section covers the theoretical foundations of climate change adaptation economics. Seen from a global climate policy perspective, the relative roles of mitigation and adaptation need to be jointly determined and they are generally substitutes. The relative costs and effectiveness of mitigation and adaption activity, adjusted for distributional concerns, determine whether more effort needs to go into one option or the other. If mitigation is cheaper and more effective, then adaption needs play a smaller role and vice versa. IAMs at the global scale have been used to address this issue (Bréchet et al., 2013).

From the perspective of a small country or local community or other potential adaptation actor, 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. Adaption action will be designed to address residual climate change but should also take into account potential complementarities with mitigation and non-climate policies. A city, for instance, that has committed to achieving a carbon emission limit can seek actions through which its mitigation policy also improves the city's ability to adapt. For example, building structures using materials that provide better insulation may reduce energy use while also protecting citizens from higher temperatures. In theory 'optimal adaptation' should seek to find the balance between adaptation and residual climate change while exploiting ancillary benefits and complementarities with other policies.

Naturally, the need for climate change adaptation policy implies a failure on the part of existing institutions to ensure adaption in accordance with welfare objectives. Economic theory considers the reasons why private actors are an important part of adaptation, but may not reach the levels of activity needed, or may respond in ways that heighten overall vulnerability (maladaptation), or on their own may be unable to provide an adequate response. There are market failures that will prevent private actors from taking the kinds and levels of adaptive actions desired. This section discusses the ways in which private adaptation takes place, as well as the various market imperfections and barriers that can hinder private actors from taking efficient action for adaptation.

The failure of private or market adaptation also provides a rationale for public action, whether in the form of correcting the market or incentivizing private action for adaptation, or supplanting the market through the provision of adaptation that is a public good in nature. This section also provides the theoretical underpinnings of public adaptation action. The role of the authorities in correcting market failures forms the basis for the choice of policy instruments that are addressed in Section 6.5.

In addition to market failure, there is a need to consider the ways in which public authorities also fail to take appropriate adaptation action. The literature is much more limited on this question, although the Fifth Assessment Report (IPCC, 2014) gives far greater prominence to the need to better understand the political economy of climate change policy. This relatively new literature will also be presented and connected wherever possible to the adaption question.

The big picture

The benefits of adaptation involve the reduction in damages from climate change along with any climate-related gains (World 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: the world can take action to mitigate climate change, or it can adapt to a changing climate. The ideal would be to choose the mix of mitigation, adaptation and residual climate damage that minimizes the total welfare loss associated with climate change. The relative roles of adaptation and mitigation in the global response to climate change are very important. The two kinds of actions are generally seen by policymakers as complements, with an optimal response combining elements of both (Watkiss et al., 2015). In strict economic terms, they are more like substitutes, with the reduction in the cost of one likely to lower the demand for the other (Ingham et al., 2005, Buob and Stephan, 2013). If adaptation is cheap and effective, there is less of a need for mitigation, or its marginal benefit falls. In considering the mix of adaptation and mitigation, we should keep in mind the limits to what adaptation can achieve, especially if climate risks are severe (Adger et al., 2009, Dow et al., 2013).

While at this broad global level, adaptation and mitigation look like substitutes, at the level of specific actions, mitigation, adaptation and non-climate activity can also be complementary (in the economic sense of the term). For instance, better insulation can help house dwellers to adapt to heat, reduce air conditioning (emissions) and be undertaken for non-climate reasons (cheaper). Allowing for distributional impacts through weightings of benefits and costs, economic theory would equalize marginal social returns to all forms of expenditures that reduce climate change damages (Musgrave and Musgrave, 1973, Brent, 2006). Whatever the mix of mitigation, adaptation and non-climate activities, there will be a need for coordination as they each may compete for scarce resources and with consumption. Ongoing crop production could be squeezed out by biofuels (mitigation) or a shift from crops to livestock (adaptation). The broader the set of activities that are considered for adaptation, mitigation and non-climate purposes, the lower the total cost of climate change (de Bruin et al., 2009a, Koetse and Rietveld, 2012, Wang and McCarl, 2013).

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. To make it concrete, a decision to allow the global mean temperature anomaly to reach 1.5 °C by mid-century would be based on an understanding of what each country will do in terms of adapting to climate change and how much this will cost them, as well as the costs of residual damage. The inherent jointness of these decisions makes the mitigation and adaptation activities of all actors at this level of aggregation a world collective choice issue.

For this theoretical exercise, the high level of aggregation of IAMs makes them the models best suited to study the trade-off between adaptation costs, mitigation cost and residual damages (for a theoretical exposition, see Bréchet et al., 2013). These models confirm that effective action involves both adaptation and mitigation (de Bruin et al., 2009b, Agrawala et al., 2011b, Bahn et al., 2012), although 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.

Higher discounts have a stronger effect on mitigation, while climate uncertainty may favor later adaptation. Fankhauser (2017) points out that the adaptation–mitigation link has theoretical interest, but international decision making is not at the point where such fine-tuning is relevant. Yet the adaptation–mitigation trade-off continues to attract attention in particular sectors, e.g., Kopytko and Perkins (2011) on energy and Rosenzweig and Tubiello (2007) on agriculture. Even though decisions on international action on climate change may not be informed by an appraisal of the mitigation–adaptation trade-off, whatever decisions do take place on mitigation implicitly determine the role for adaptation.

Most adaptation actors are also emitters of GHGs, but their carbon output is generally too small to have a tangible impact on the global climate so they are generally climate takers; they take adaptation action based on a perceived change in climate. This is certainly the case for many (small) countries that can have only a very limited impact on global emissions. From their perspective, the level of mitigation has largely been determined by an international or regional agreement, and/or by a country's or actor's own initiative.

In such a context, the extent of adaptation policy is mostly a choice between taking action to adapt and thus ameliorate the damage from climate change, and allowing residual climate change damage. The choice and nature of adaptation action should still be coordinated with mitigation and non-climate activity, since there will still be complementarities to exploit, as previously discussed. As far as mitigation is concerned, the question will not be how much to mitigate, but how to achieve a mitigation target set at the least cost. To put it differently, while a small country will not need to consider the trade-off between its mitigation and adaption policy, it should consider the ways in which domestic mitigation and non-climate activities interact with adaptation, e.g., the ancillary benefits of adaptation policy.

- Sea walls that protect against sea level rise and at the same time protect against tsunamis. However, they can have co-costs causing damages to adjacent regions, fisheries, and mangroves (Frihy, 2001).
- Crop varieties that are adapted to climate change have enhanced resistance to droughts and heat and so also raise productivity in non-climate change-related droughts and temperature extreme (Birthal et al., 2011).
- Better building insulation that mitigates energy use and associated GHG emissions also improves adaptation by protecting against heat (Sartori and Hestnes, 2007).
- Public health measures that adapt to increases in insect-borne diseases also have health benefits not related to those diseases (Egbendewe-Mondzozo et al., 2011).
- More efficient use of water -- adaptation to a drier world -- will also yield benefits under current conditions of water scarcity.
- Development of improved desalination methods has the same merits (Khan et al., 2009).
- Locating infrastructure away from low-lying coastal areas provides adaption to sea level rise and will also protect against tsunamis.
- Reducing the need to use coal-fired power plants through energy conserving adaptation will also provide mitigation, improve air quality, and reduce health impacts (Burtraw et al., 2003).

Box 6.1. Ancillary economic effects

Source: Chambwera et al., 2014, page 951.

Many studies argue for the need to incorporate co-benefits into decision making (Brouwer and Van Ek, 2004, Ebi and Burton, 2008, Qin et al., 2008, de Bruin et al., 2009a, Kubal et al., 2009, Viguié and Hallegatte, 2012). See Box 6.1 for examples of ancillary economic effects (Chambwera et al., 2014).

Figure 6.1 from Chambwera et al. (2014, Figure 17-2) provides a very interesting graphical representation of the link between the cost of climate change (vertical axis) and the cost of adaptation (horizontal axis). The figure shows that if there is no adaptation, then society will bear the full cost of climate change. One way to reduce that cost is by adapting. Some initial forms of adaptation may be costless (free adaptation), such as changing the sowing dates of crops. Beyond some point, adaptation will incur costs and, in an ideal world, adaptation effort would continue up to the point at which the cost of additional adaptation is equal to the cost of climate change. Any additional adaptation from this point onward would cost more than the benefits gained, so some level or residual climate costs will exist.

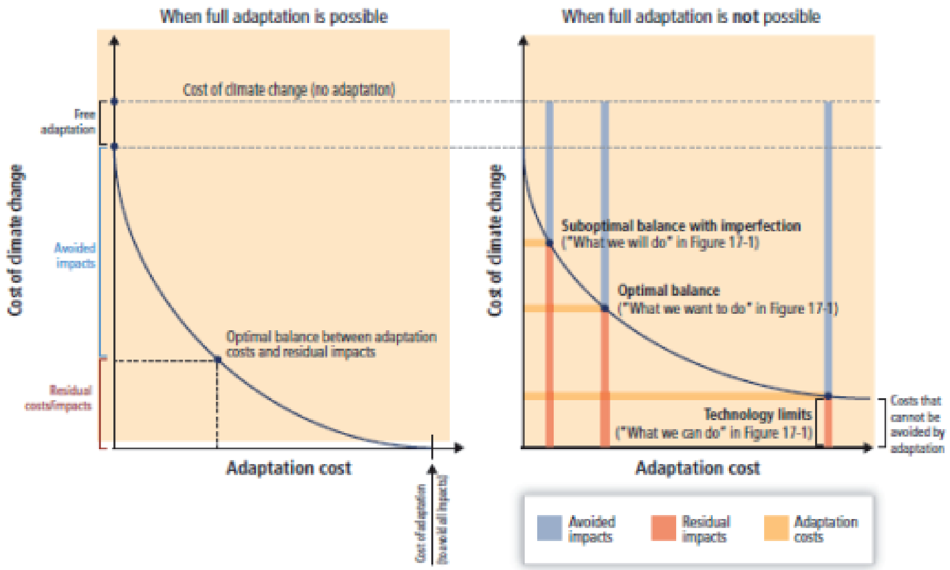

Figure 6.1. Climate change and adaptation costs

Source: Chambwera et al., 2014, "Economics of adaptation", in *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects*, Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK and New York, NY, Figure 17-2.

Barriers or constraints to adaptation (institutional failures) may prevent achievement of the optimal balance between climate costs and adaptation costs. There will also be technological limits to what climate change costs can be avoided, in which case the optimal balance is between avoidable climate change costs and costs of adaptation. (See de Bruin et al. (2009b) for more on the relationship between adaptation effort and residual damages.)

There are conceptual issues in discerning an adaptation activity or project. Activities may help to reduce the cost of climate change without being undertaken explicitly for that purpose, e.g., new building codes, while explicit adaptation activity may have ancillary benefits and or may be undertaken to exploit opportunities. When trying to determine the extent to which an action involves adaptation or additional expenses for adaptation, a baseline needs to be defined. How much has the activity in question reduced costs of climate change? This implies knowledge of what costs would have been incurred in the absence of adaptive activity or the absence of the adaptive component of projects that may have been undertaken anyway.

6.2.2 Private adaptation

Economic activities are generally exposed to climate factors either directly or indirectly. Adaptation by private agents will take many forms and be widespread. Although this form of adaptation has often been called ‘autonomous’, according to Fankhauser (2017) this is a misnomer as all adaptive activity is the result of deliberation and often complex decisions. Chambwera et al. (2014) continue to make the distinction between autonomous, planned and natural adaptation actions. Natural adaptation refers to those actions occurring within the ecosystem that could also be subject to human intervention. Autonomous action is said to be undertaken mostly by private parties. Perhaps the ‘autonomous’ is meant to allow for non-deliberate action in the sense of things people do in view of new rules, norms or codes of conduct that may not consciously involve the pursuit of adaptation but still have that effect.

Additionally, all interactions that take place through the market price system, such as when tourists shift their vacation location or timing choices in response to changing temperature and weather conditions, have ramifications that work through the price system (pricing of hotels, energy demands, services provided in new locations and so forth). Much of this market activity may appear autonomous or non-deliberate, but we can use the term ‘private’ adaptation (deliberate or not) to cover all actions that are undertaken by agents privately and through the market.

Private adaptation refers to actions that firms and individuals take for their own sake in response to climate change. An individual's utility includes weather and climate and this will affect choices of both consumer goods and consumer durables. To the extent that weather or climate affects the quantity of a good demanded, e.g., consumption of more fluids and air conditioning, these goods are a part of the adaptation strategy of households. Changes in consumption goods can be defined as *intensive changes*, such as drinking more water on a hot day or increasing the use of the air conditioner, while changes in durable goods are *extensive changes*, such as investment in insulation or purchasing a new air conditioner. A decision to insulate the house (extensive change) may lead to a reduction in use of electricity (intensive change). Evacuating in view of a coming storm is an intensive change while fortifying a home in view of coming storms is an extensive change (Massetti and Mendelsohn, 2015).

Efficient private adaptation implies that individuals maximize their net benefits by adjusting consumption and durable goods in response to weather and climate change. Likewise, climate and weather variables enter into a firm's production function and this will affect the optimal choice of inputs. Farmers can adapt to weather by changing their use of fertilizer, labor and irrigation water. For instance, bad weather would lower productivity of crops and so lower the marginal productivity of complementary inputs such as fertilizer or labor. The optimal response would be to reduce inputs per unit output. This would be a response on the intensive margin. An investment in capital, such as irrigation to overcome water shortages, would involve adaptation along the extensive margin. Even if firms adapt efficiently to climate change, it does not mean that they will necessarily be better off or have higher profits, but rather that they are doing the best they can given the changes (Massetti and Mendelsohn, 2015).

Economic models can be used to see how agents will behave in different climate conditions and thus gauge adaptive behavior. In this sense, models can be used to study how actors react to climate change as it unfolds, but they can also study what agents might want to do in advance of climate change. The same models used to explore the impacts of price changes on agents' decisions can be used to see how decisions are affected by a changing climate or how they should be made in view of climate risks.

Dynamic models are particularly important when adaptations require large adjustments in slow-moving stocks of capital, e.g., coastal protection and timber. Models can determine the optimal dynamic response changes taking place over time, such as deciding how to respond to a gradually rising sea level through protective coastal structures.

In forward-looking models, agents are assumed to have perfect foresight and can use deterministic models to calculate how to adapt in advance to climate change. Sohngen and Mendelsohn (1998), for instance, model the impact of climate change on the timber market and this is anticipated by agents that can take adaptive action accordingly. These models can be made slightly more sophisticated by treating future effects as uncertain events with known probability distributions. Agents with sufficient access to capital can find optimal adaptation strategies by taking the expected values of outcomes. If information about the future becomes available over time, stochastic dynamic programming would be required to determine adaptive strategies while learning over time. Stochastic dynamic programming models suggest a more flexible strategy that takes advantage of newly-available information over time (Massetti and Mendelsohn, 2015).

Failure of private adaptation

Despite evidence of beneficial private adaptation, there are good reasons to expect that the response of agents to climate risks may be inadequate, ineffective or even lead to worse outcomes (maladaptation). Many barriers to private adaptation or causes of failure in private adaptation have been identified. These include causes of market failure even when agents behave rationally, or failures in the behavior of agents (Repetto, 2008, Cimato and Mullan, 2010, Moser and Ekstrom, 2010, Biesbroek et al., 2011, 2013). The list of causes of such failures can be large.

Transaction costs are a broad category of costs related to accessing information and markets, setting up property rights and enforcing them, and costs of bargaining (Coase, 1937, 1960, Williamson, 1979). Transaction costs may prevent certain beneficial adaptation activities from taking place. Information on climate and weather data may be costly or difficult to access (Cimato and Mullan, 2010, Ford et al., 2011, Scott et al., 2011). The difficulty of accessing this information is one problem faced by private agents but, in addition, information involves externalities.

Positive externalities and the public good nature of many adaptation goods is one important cause of market failure leading to inefficient private provision. Knowledge and research are typical examples that involve externalities. The public good nature of climate and weather information is a bigger problem, however, in that while the total benefits may greatly outweigh the costs of provision, private actors will not be able to capture the total benefits. This provides a rationale for public authorities or organizations to support production and dissemination (Fankhauser et al., 1999, Mendelsohn, 2000, Trenberth, 2008). Investment in knowledge and research can have many benefits beyond those that can be monetized through patents or early exploitation of some new idea. In addition, patents can lead to monopolies of ideas or technology that, while incentivizing private research, may stunt the broader use of them.

Another important source of market failure is the lack of well-defined or adequately secured property rights. In such cases, households or firms may not have the needed incentives to undertake private adaptation. If individuals are not sure about their title to a piece of land, they may not invest in the land to adapt to changing climate. Governments can play an important role in better protecting and enforcing property rights. Asymmetric information between buyers and sellers about the risk profile of dwellings can also lead to failures in these property markets. Inadequate abstraction rules or low water prices have also been identified as preventing appropriate adaption in water management (Agrawala, 2005, Agrawala and Fankhauser, 2008).

Insurance coverage may give rise to moral hazard, with agents ignoring or taking inadequate precautions with respect to climate risks. To the extent that flood risks are partly assumed by insurance or post-disaster support, a community may not undertake flood mitigation measures. This is an instance of moral hazard (Burby et al., 1991, Laffont, 1995).

Other externalities may hinder adequate adaptation action, such as when one agent's adaptation actions may create damages for others. In the case of irrigation, for instance, one country creates water scarcity to another downstream country (Goulden et al., 2009). If there are large fixed costs or increasing returns to adaptation activity, there may be insufficient investment (Eisenack, 2014). Public action through a number of policy forms (direct public investment; economic instruments such as taxes; coordination at regional, national and international levels) may be required in the case of such failure of market or private adaptation.

Another source of potential failure of private adaptation derives not from the failures in market institutions or the nature of adaptation goods, but in 'failures' of human behavior. While economic agents adapt continuously to climate conditions, they may not use available information, especially for consequences that are distant in the future (Camerer and Kunreuther, 1989, Thaler, 1999, Michel-Kerjan, 2008). When faced with ambiguous choices, individuals may defer decisions (Tversky and Shafir, 1992, Trope and Liberman, 2003) or make choices that are time inconsistent by, for instance, 'hyperbolic discounting' (Ainslie, 1975). Individuals have been found to systematically favor the status quo and familiar choices (Johnson and Goldstein, 2003), and to value gains and losses differently (Tversky and Kahneman, 1975).

Availability heuristic refers to the tendency that humans have to judge an event by the ease with which it can be retrieved from memory or constructed anew (Marx and Weber, 2012). With the slow rate at which people update their views or adjust their mental models, Szafran et al. (2013) show by simulation using US weather station data that if people require three consecutive years in which maximum temperature is a full standard deviation or more above the historical high, it would take 86 years for them to adjust their mental model. Cognitive barriers can be expected for complex, probabilistic adaptation decisions, as shown in two case studies by Grothmann and Patt (2005). Even in large organizations there are limitations in perception, resources and capabilities that prevent adaptive action from getting the attention of senior management (Berkhout, 2012). Hong et al. (2016) find that stock markets fail to factor climate risks into their valuations.

More generally, all of these cognitive attributes raise questions about the extent to which individuals are likely to make good decisions about adaptation. Policy needs to account for these behavioral tendencies by drawing on psychological and social insights. Local mental models and narratives can be incorporated into communication strategies. Climate forecasts could be made more intuitive. Social norms can be used to assist adaptive choices (World Bank, 2014).

Failures of private adaptation are likely to be even more accentuated in low-income countries and populations. Lack of institutional, financial and technological capacity deprive private agents of the necessary scaffolding to undertake effective adaptive activity. These factors also point out the complementary nature of the public and private spheres of activity. The institutional structures of a country or local community can play a critical role in enhancing the adaptive potential of private and other non-governmental agents.

Adaptive capacity issues are a problem for both private and public adaptation. Understanding this **adaptation deficit** or **adaptation gap** in adaptive capacity has attracted considerable research. Factors that can hinder the capacity to adapt include income, literacy, income distribution, institutional quality, access to financing, health spending and household size (Kahn, 2005, Noy, 2009, Di Falco et al., 2011, Fankhauser and McDermott, 2014, McDermott et al., 2014). More work needs to be done to augment the list and understand potential interactions between these factors (Fankhauser, 2017). While most measures of adaptive capacity add up certain contributing factors (Brooks et al., 2005, Barr et al., 2010), others suggest that it can be measured by those factors least developed (weakest link) (Tol and Yohe, 2007). Adaptive performance differences have also been found among sectors (Carleton and Hsiang, 2016).

The issue of an adaptation gap is closely related to the broader link between development and adaptation. Development itself has been seen as a key form of adaptation to climate change in poorer countries (Schelling, 1992, Tol, 2005, Mendelsohn, 2012). If development shifts the share of the economy away from climate-sensitive sectors such as low input agriculture to sectors that are less vulnerable to climate change, then development can be seen as part of an adaptation strategy. Fankhauser and McDermott (2016), however, point to important differences between development and climate-resilient development. Even though development will generally increase the level of adaptation, it can also increase vulnerability and exposure, depending on the choice of development paths.

While many of the market failures presented here suggest the need for government correction of the markets or direct government adaptation activity, governments themselves can also be a cause of market inefficiencies through policies that distort market prices. They can create barriers to trade which may prevent market response to shocks such as climate change (Reilly et al., 1994). Reducing government distortions may play a role in helping private adaptation.

6.2.3 Public adaptation

Even though agents find ways to adapt to a changing climate, there are good reasons to expect that some of these activities will be inadequate or fail to produce the best adaptive response. Imperfect private adaptation provides a rationale for government action to find means to correct market or other institutional failures. Some benefits of adaptation are in the nature of public goods in that they are jointly consumed by many individuals and firms. Typical examples are 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, or climate proofing of conventional public goods such as transport networks (Dietz et al., 2016).

Provision of these public goods will generate benefits to many. To the extent that the parties undertaking adaptation activities cannot capture all the benefits associated with their actions, there is likely to be underinvestment in these actions. Markets generally fail to provide public goods at levels that are efficient, since many can enjoy the benefits without paying for them or revealing their willingness to pay. This is a classical result in economic theory (Samuelson, 1954) but experience and observation regarding adaptation (Mendelsohn, 2000, Osberghaus et al., 2010, Wing and Fisher-Vanden, 2013) also attest to its empirical relevance. In such cases, the government is called upon to correct this market failure and to attempt to determine the optimal level of public adaptation.

As is standard in welfare economics, market failures (or barriers) provide a theoretical justification for public policy in the form of corrective measures so that incentives ensure that private adaptation will be effective and efficient. Moreover, market failure in the provision or climate proofing of public goods that enhance climate resilience implies that the private sector lacks incentives to provide for them, and therefore similar incentives are neeeded. Interestingly, while there is a generally agreed upon toolkit for such corrective policies for climate mitigation policy, nothing similar exists for adaptation policy. Corrective policies for adaptation come mostly in the form of refinements or mainstreaming of existing policy interventions in the context of sectoral policy, e.g., coastal zone planning, integrated water resource management, water pricing, weather insurance and payments for ecosystem services (Agrawala and Fankhauser, 2008, Fankhauser, 2017).

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. There is a need for capacity building, technical assistance and help with response plans in poor countries or among poor populations where an adaptation gap is likely (Watkiss, 2016). Castells-Quintana et al. (2016) point to the need for social safety nets to aid post-disaster recovery. In the case of distributional issues, it is known that the impacts of climate change will vary greatly by social group, with the poor being particularly vulnerable (Stern, 2007, Füssel et al., 2012).

Traditionally, economists separated distributional from efficiency issues on the assumption that distributional aims could be attained by appropriate costless financial transfers, while projects could be appraised purely on efficiency grounds (Brown and Heal, 1979, Atkinson and Stiglitz, 1980). This dichotomy has come into question due to the rise of information economics (Stiglitz, 1994, Arnott et al., 2003). In terms of project appraisal for adaptation decisions, this points to the need to jointly account for efficiency (net benefits) and equity concerns (Aakre and Rübbelke, 2010).

Failure of public adaptation

The fact that the market cannot be expected to deliver public goods efficiently does not mean that the government will be an efficient provider of public adaptation goods. There are challenges for determining the efficient level of public goods provision, such as determining the total benefits arising from them, but there are also reasons for government failure. Governments may be subject to influence from interest groups that could either lead to overinvestment in certain adaptation goods, such as when coastal protection structures cater to influential individuals even if the costs outweigh the benefits, or underprovision when benefits are individually small or dispersed widely or are distant in time and do not provide electoral benefits.

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 by helping with behavioral and cognitive biases – they are also prone to failures (Krueger, 1990). The traditional view of government as a benevolent authority has been questioned by many political economy perspectives that recognize that government agents may pursue more narrow personal gains (electoral success) and be subject to influence by powerful lobbies. As mentioned above, interest groups could either lead to overinvestment or underprovision in adaptation. The political economy view of the government has played a much more prominent role in the literature on mitigation policy, as evinced by the latest IPCC (2014) report, and its importance is not just to question the effectiveness of public policy, but also to consider what implications there are for designing policies that are likely to be sustained in a given political context. There is much less literature on the political economy of adaptation.

There are a number of other potential sources of public adaptation failure. Moral hazard may afflict subnational entities where central government support can be taken for granted in case of disasters (Michel-Kerjan, 2008). In poorer countries, limited access by governments to capital markets, other resource constraints, or adaptation capacity problems, can prevent them from undertaking adaptation projects that have net benefits (Brooks et al., 2005, Smit and Wandel, 2006). Coordination problems can be another important cause of failure, especially in the context of adaptation policy that requires multi-ministry actions. Finally, in addition to government failure that may emanate from rational public servants and representatives, cognitive limitations and biases may also lead to failures in public adaptation. Decision makers in positions of public authority may be liable to the same biases attributed to individuals in general (Podsakoff et al., 1990, Viscusi and Gayer, 2015).

The list in Box 6.2 shows the broad categories of adaptation strategies, and who might carry them out (Chambwera et al., 2014). As is clear from this list, adaptation activity need not be costly, as it may involve changes in recurring expenditures such as replacing depreciated equipment with more adapted equipment, or changes in behavior and lifestyles.

- Altered patterns of enterprise management, facility investment, enterprise choice, or resource use (mainly private)
- Direct capital investments in public infrastructure (e.g., dams and water management – mainly public)
- Technology development through research (e.g., development of crop varieties – private and public)
- Creation and dissemination of adaptation information (through extension or other communication vehicles – mainly public)
- Human capital enhancement (e.g., investment in education – private and public)
- Redesign or development of adaptation institutions (e.g., altered forms of insurance – private and public)
- Changes in norms and regulations to facilitate autonomous actions (e.g., altered building codes, technical standards, regulation of grids/networks/utilities, environmental regulations – mainly public)
- Changes in individual behavior (private, with possible public incentives)
- Emergency response procedures and crisis management (mainly public)

Box 6.2. Broad categorization of adaptation strategies

Source: Chambwera et al., 2014, p. 950.

6.3 Analytical and empirical methods of studying adaptation

Many of the same tools used to understand the impacts of climate change and evaluate alternative mitigation policies are also used to understand 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. There are demands on the analytical and empirical tools that are unique to adaptation issues and these will be the focus of this section. Most of these models are presented in other chapters of this book, but here we will focus on their role or potential role in addressing questions of interest for adaptation policy.

6.3.1 Integrated assessment models

Integrated assessment models (IAMs) can be used from a global perspective to determine the optimal mix of mitigation and adaptation over time (de Bruin et al., 2009a, Bosello et al., 2010). The first IAMs featured adaptation only indirectly in the damage function (a stylized representation of climate change impacts). The least-cost combination of adaptation costs, AC, and residual damages, RD, was meant to be captured by the following damage function, $D(T)$:

$$D(T) = \arg\min_A [AC(A,T) + RD(A,T)],$$

where A is adaptation effort and T is global mean temperature.

This damage function, however, was not explicitly modeled and adaptation was simply assumed to be optimal. Estimates of adaptation costs (related to coastal protection and changes in energy demand) were combined with estimates of residual damages (e.g., changes in agricultural yields) to make up the damage function. By assuming that adaptation was optimal, modelers could focus on other issues such as mitigation (Fankhauser, 2017).

Some prominent IAMs have been modified to create adaptation-IAMs that jointly optimize adaptation and mitigation action across mitigation costs, adaptation costs and residual damage. There are modifications of IAMs based on DICE/RICE (de Bruin et al., 2009a, 2009b, de Bruin and Dellink, 2011), the WITCH (Bosello et al., 2010), and a combination of both of these (Agrawala et al., 2011b).

On the other hand, according to Fisher-Vanden et al. (2014, p. 495), "no study has accounted for the implications of impacts and adaptation for the climate stabilization strategies". There are a number of ways in which the omission of adaptation responses from analysis can bias the results:

1. The economic costs of climate impacts can be dampened by adaptation;
2. The baseline emission trajectory could be changed by adaptation, e.g., the use of air conditioning could increase emissions; and
3. Investments in adaptation could crowd out mitigation and thus make it more expensive.

The standard reason offered for not incorporating adaptation responses into IAMs is the inadequate empirical basis to characterize them. There is growing empirical research that could provide the basis but it remains unexploited, partly because the econometric studies are reduced form while the IAMs are structural models, and partly because the impacts and adaptations studied by econometric models are at a higher level of detail than typically used in IAMs (Fisher-Vanden et al., 2014).

Biophysical impacts of climate change will be heterogeneous in both attributes and geographical incidence, so both the nature and magnitude of shocks will differ across regions. Certain sectors are also likely to be more vulnerable than others, and defensive expenditures will likely target particular sectors and regions anticipated to be particularly exposed and vulnerable. IAMs therefore need to contain sufficient regional and sectoral detail to capture these adaptation decisions or to find a way to consistently aggregate this detail to a coarser spatial scale.

The form of adaptation must also be accounted for by IAMs. A few IAMs are able to simulate *passive* adaptation that is part of the general market reactions, e.g., shifts in tourism timing or destination due to changes in temperature. *Reactive* adaptation investments such as treatment of vector-borne disease, and *proactive* adaptation investments, e.g., early warning systems, also need to be incorporated into IAMs at the requisite regional and sectoral level of climate impacts (Wing and Fisher-Vanden, 2013).

The difficulties that IAMs have in modeling intertemporal decision making under uncertainties mean that endogenous investment in proactive adaptation measures such as coastal protection has not been captured. IAMs need to be made capable of capturing trade-offs between the opportunity cost of investments today and avoided future damages. Technological improvements in adaptation-related activities in response to increasing demand for adaptation also need to be accounted for by IAMs. The regional and sectoral specificity of adaptation measures might limit the market for new adaptation techniques and thus reduce the role of private R&D and increase the need for public investment. IAMs also have to account for the revenue-easing mechanisms that supply investment funds (Wing and Fisher-Vanden, 2013).

Wing and Fisher-Vanden (2013, Figure 1) provide a conceptual framework of the needed modifications to IAMs. Specific protective or defensive measures such as drought- and heat-tolerant varieties of crops (referred to as Type II adaptation activities) will moderate the response of sectoral productivities to the character and magnitude of the physical impacts. Adaptation that lessens the adverse effects of impacts that do occur on the productivity of some sectors includes investments in disaster preparedness, response and recovery, insurance, and redundant or flexible production capacity (referred to as Type III measures). For given levels of these adaptation activities, the magnitude of damages will also depend on price changes and substitution responses across many markets (referred to as Type I 'passive general equilibrium adjustments'). These three types of responses interact with one another and are jointly influenced by the magnitude and character of climate impacts that induce the need for adaptation in the first place. A quantification of climate impacts and responses must start with how climate change variables impact key endpoints at the regional level which in turn impact sectoral productivity shocks (Wing and Fisher-Vanden, 2013).

6.3.2 Empirical analysis

Support of adaptation decision making at the sectoral level usually relies on studies that follow an econometric or simulation approach. Much work has been undertaken to understand and document the way in which economic agents respond to climate and weather. Detailed and often interdisciplinary case studies help illuminate these questions on such matters as migration (Penning-Rowsell et al., 2013) or insurance (Ranger and Surminski, 2013). Increasingly, researchers use large data sets (at the household, firm or farm level) to explore adaptation of economic agents. Dell et al. (2014) and Hsiang (2016) provide surveys of the climate econometrics and their methodological challenges.

Econometric studies examine observed responses of agents to climate or weather. Cross-sectional, time series or panel data are used. Cross-sectional studies have also been used to explore how weather and climate affect demand (Massetti and Mendelsohn, 2015). In this 'Ricardian approach', it is assumed, for instance, that farmers have adapted to changes in temperature and precipitation and that this will be reflected in land values and crop yields (Mendelsohn et al., 1994, Schlenker et al., 2004). Since many factors vary across space, the challenge is to distinguish variation associated with climate (Deschênes and Greenstone, 2007). Farmers have been found to adjust crop (Kurukulasuriya et al., 2008) and livestock (Seo and Mendelsohn, 2008c) across locations. These studies can only capture the long-term steady states and not adjustments of agents through changing conditions. They compare endpoints in adaptation processes and therefore cannot illuminate the actual costs and benefits of adaptation, or the adaptation decisions themselves, through time. Furthermore, separating confounding factors that also vary across space, such as history and institutions, can raise substantial analytical challenges (Fankhauser, 2017).

In time-series analysis, spatial factors remain constant (institutions, culture, etc.), and weather variations are clearly exogenous, making identification easier. This analysis can do well with short-term observable variations, but will have difficulty capturing long-term climatic factors. Similarly, short-term adaption responses will be identified rather than long-term adaptation.

Panel models cannot easily measure adaptation to climate, as fixed effects remove time invariant variables such as climate, but they are good at finding the impact of weather (Dell et al., 2014). Panels can be compared in different periods but we need to be sure to observe climate change and not random weather shocks (Burke and Emerick, 2016). Panel data can isolate long-term adaptation on short-term shocks by interacting weather fluctuations with average climate conditions (Deschênes and Greenstone, 2011, Hsiang and Narita, 2012). Studies that focus on weather trends over longer periods can also identify long-term adaptation (Burke and Emerick, 2016).

The econometric approach has the advantages of using real-world data, and the ability to capture the costs and benefits of multiple adaptation strategies when used together (Mendelsohn and Neumann, 1999). There is no need to model all potential adaptation mechanisms as the approach relies on the relationship between a climate stressor and an outcome of interest. From another perspective, this approach has the disadvantage that it cannot isolate the implications of specific adaptation strategies. We also cannot transfer estimates out of context to other regions where climate and social context differ. Moreover the statistical estimation can be challenging (Schlenker et al., 2004).

Controlled experiments by agronomists and engineers are a standard way of finding climate outcome links. Agronomists use controlled experiments to study how temperature, precipitation and CO_2 affect crop yields. Engineers have looked at how outside temperature changes affect the electricity needed to preserve a constant indoor temperature level. These experimental studies generally omit adaptation, but they provide evidence for adaptation such as showing how climate enters into production functions (Massetti and Mendelsohn, 2015). In principle, they could also be used to explore the effectiveness of adaptation strategies.

6.3.3 Economy-wide simulation

Cross-sectional analysis and panel models detect adaptation at the level of the individual and what choices individuals make, e.g., crop selection. Much adaptation will work its way through markets through shifts in demand and supply responding to climate impacts. If climate change reduces the supply of some good, its price will increase. This will stimulate increases in production (countering the initial supply shock) as well as dampening consumption. Calibrated simulation models can be used to capture these market responses. Mathematical programming can simulate the market impacts of yield changes (Adams, 1989). General equilibrium models can be used along with crop models to detect market adaptation (Reilly et al., 2003, Rosenzweig and Tubiello, 2007).

Market adaptation to climate change at a global level can be measured by macroeconomic models (Wing and Fisher-Vanden, 2013). Partial equilibrium models are used to capture market adaptation at a sectoral level; see, for example, Adams et al. (1995) for agriculture and Sohngen and Mendelsohn (1998) for the timber market.

The way in which an economy adjusts to climate shocks (e.g., through changes in relative prices) is an important form of adaptation (Fisher-Vanden et al., 2013). The response to climate change in one sector of the economy, such as agriculture, will affect related sectors, such as food processing and textiles. As farmers flee floods and move to urban areas, they will depress wages in cities and the price of the land they abandoned. Other agents will respond to these price changes as the economy moves from one equilibrium to another (Banerjee, 2007).

CGE models, macroeconomic models and input-output models can be used to capture these economy-wide repercussions. These models also allow an appraisal of the combined effects of adaptation to simultaneous climate risks (Eboli et al., 2010, Christensen et al., 2012). Explicit use of economy-wide models for adaptation is still relatively rare. Although there is some evidence that higher-order effects may exacerbate initial effects (Berrittella et al., 2006, Bosello et al., 2007, Hallegatte, 2008), it is still generally not clear what the direction of effects will be. Agriculture is the only area in which indirect effects have been studied (Reilly et al., 1994, Reilly et al., 2007, Nelson et al., 2010).

The structure of system-wide models does not necessarily fit well with the demands of adaptation analysis. It is difficult, for instance, to incorporate the effects of droughts and floods, or water supply changes, into social accounting matrices or input-output tables. Also, general equilibrium models can be used to compare two static equilibria once the economy has had time to adjust in the long term, but not the short-term costs of a shock (Fisher-Vanden et al., 2013).

Given the increasing interconnectedness of economies, system-wide indirect effects may turn out to be more important than direct effects for some sectors, so there are compelling reasons to overcome the modeling challenges. Some evidence for the importance of indirect effects can be found in the study of wider climate risks embedded in a typical consumption basket in the UK (ASC, 2014).

The simulation approach models a number of components in the chain of impacts starting from climate change, the impacts on the biophysical attributes of interest (e.g., precipitation and temperature), and the behavioral-economic component. The behavioral-economic component may incorporate rational responses by actors or a decision-rule type response to climate stressors. Simulation modeling requires extensive data inputs and calibration. Its advantage is that it can provide appraisal of how specific adaptation strategies at various intensities can affect outcomes, such as finding the change in crop output and water supply resulting from water resource management techniques used to respond to climate change.

6.3.4 Decision-making tools

A standard approach used in project appraisal is cost-benefit analysis (CBA), which requires that the evaluations be in monetary terms. Even when focusing on market impacts, there is a need to correct for price distortions arising from policies, market structures or other causes of market failure (Squire and van der Tak, 1975). Many costs and benefits involve non-market impacts on environmental quality and ecosystems, public health or distributional concerns, and as such they need to be translated into monetary values. Valuation techniques for non-market impacts face many challenges and controversies, especially as regards health and mortality (Viscusi and Aldy, 2003).

When decision makers have multiple objectives and have difficulty striking a balance between them, multi-metric or multi-criterion analysis can provide a useful framework (Keeney and Raiffa, 1993, Martinez-Alier et al., 1998). A full range of criteria (social, environmental, technical and economic) are quantified and trade-offs are displayed. There are many applications of multi-criterion analyses to adaptation issues. See, for example, Kubal et al. (2009) and Viguié and Hallegatte (2012) for urban flood risk and Julius and Scheraga (2000) for agricultural vulnerability. For applications to adaptation options in different countries, see Brouwer and Van Ek (2004) and de Bruin et al. (2009a) for the Netherlands, Qin et al. (2008) for Canada, and Smith and Lenhart (1996) for Africa.

Uncertainty of varying types and extent plays an important role in determining the right decision-making tool. A number of economic approaches to decision making under uncertainty have been applied to adaptation issues. Fankhauser (2017) provides a very useful overview of the uncertainty appraisal tools. CBA uses subjective probabilities for different climate futures and selects the project that maximizes the expected net present value. Risk aversion can also be taken into account. One important question has to do with the timing of adaptation activity. The (decades) long-term horizon and iterative process of adaptation contrasts to the normal time framework for development planning. This raises the question of how to prioritize and sequence adaptation interventions over time.

Fankhauser and McDermott (2016) suggest an obvious way to undertake this task, in terms of comparing the net present value of an adaptation investment at different times. They identify three main motivations that determine the best sequencing: the cost of action at different times; the ability to secure early benefits; or the possibility that long-term benefits may be materially affected by a delay. The first of these three motivations (the cost of action) is associated with the risk of locking in climate vulnerabilities that cannot easily be reversed. In the case of long-term investments such as infrastructure (sea ports, rail links, power stations), spatial planning (the location of housing developments) or building design (urban drainage systems), the costs of retrofitting may be higher than spending early on climate proofing. The second component (ability to secure early benefits) is associated with those cases in which an adaptation measure may provide broader environmental benefits, such as mangrove protection (Tri et al., 1998, Barbier, 2007, Das and Vincent, 2009) or measures addressing extreme weather events (e.g. Paul, 2009, Di Falco et al., 2011). The third component (delay affecting long-term benefits) is associated with adaption measures that take time to build up or come to fruition, such as research and development in climate-resilient products and processes (Miao and Popp, 2014, Conway et al., 2015) and capacity building. A number of concrete interventions related to these three motivations have been identified (Smith and Lenhart, 1996, Ranger et al., 2014, Watkiss, 2016, Watkiss and Hunt, 2016). IAMs have corroborated the importance of these motivations and provide support for building a stock of adaptation capital early on (Agrawala et al., 2011a, Millner and Dietz, 2015).

The issue of timing of action has also been addressed in the literature on uncertainty about whether to delay action in order to wait for more information. Real options techniques can extend CBA to capture this dimension (Arrow and Fisher, 1974, Henry, 1974). The extent of learning over time and whether actions are irreversible can also play an important role (Heal and Kriström, 2002). An iterative process or an option value approach is recommended in cases where uncertainty is likely to be resolved in time. For an application of these methods to flood protection in the US, see Ranger et al. (2013).

The many and often deep uncertainties related to climate change (demographic and technological trends, socioeconomic development pathways, the extent and patterns of climate change, the reaction of ecosystems, climate policies) compound each other and further deepen the overall uncertainty and can raise difficult challenges to decisions about adaptation. The long lifespan of many adaptation options, when coupled with uncertainty, can lead to increases in vulnerability or 'maladaptation'.

At one level, uncertainty can be seen as being less problematic for adaptation as compared to mitigation. The persistence of CO_2 in the atmosphere means that damage often occurs centuries after emissions, so mitigation policy has to take a very long-term perspective. Projections of climate change and damages are extraordinarily uncertain in these time frames, but mitigation must take place with these levels of uncertainty. Adaptation decisions, on the other hand, generally concern shorter time frames (Massetti and Mendelsohn, 2015). Reactive adaptation is by its nature short term, but even proactive adaptation involves investments such as dams and coastal protection infrastructure that, while long term, involve time scales far shorter than centuries. However, while adaptation activity may involve relatively shorter time scales than mitigation activity, adaptation is perhaps prone to even more uncertainty, given the more detailed regional or local scale of information required to formulate effective adaptation policy. Information for secondary climatic variables such as precipitation, wind speeds, weather extremes and seasonal variations – which is crucial for adaptation decisions – is scarcer than for global meant temperature.

The deep uncertainties associated with climate change have shed doubt on the usefulness of expected utility theory as a guide to rational climate action (Heal and Millner, 2014). An overview of various decision-making tools and heuristics proposed for adaptation decisions under deep uncertainty is provided by Ranger et al. (2010), Hallegatte et al. (2012) and Watkiss and Hunt (2016). In many cases it may be very difficult to define probabilities for alternative outcomes or identify the set of possible futures (Henry and Henry, 2002, Weitzman, 2009, Gilboa, 2010, Millner et al., 2010, Kunreuther et al., 2013a). Many climate change impact and adaptation studies use a scenario-based analysis that incorporates the uncertainty of key parameters. These can be combined with alternative decision criteria to assist decision making (Ranger et al., 2010, Hallegatte et al., 2012). Maxi-min chooses the decision which attains the best outcome under the most adverse conditions, while the mini-max regret (Savage, 1951) looks for the smallest deviation from the optimality in any state of the world. Application of a 'no regrets' adaptation approach has been employed by Callaway and Hellmuth (2007) and Heltberg et al. (2009).

The notion of **robustness** is associated with finding actions that perform well over a wide range of scenarios (WUCA, 2003, Dessai and Hulme, 2007, Lempert and Collins, 2007, Groves et al., 2008, Wilby and Dessai, 2010, Lempert and Kalra, 2011, Lempert et al., 2013, Bhave et al., 2016). These methods look at an option and test it under a large number of scenarios in order to identify vulnerabilities to uncertain parameters. These vulnerabilities are then minimized by adjusting the options or project. There are numerous examples of models used for such robust decision making in the context of water management and flood risk management planning (Ben-Haim, 2001, Lempert and Groves, 2010, Korteling et al., 2013, Matrosov et al., 2013).

6.4 Climate change impacts and adaptation: global and sectoral

This section presents the results of models on the costs of adaptation, which involves an appraisal of climate change impacts and possible adaptation responses. For the purposes of financing adaptation, models have attempted to cost adaptation at the global level. Much of the analysis of adaptation costs takes a sectoral perspective. This literature is presented here, as well as the literature that focuses on adaptation in Europe.

6.4.1 Global

The literature on determining the cost of adaptation focuses either on the global scale, mainly in order to get an overall estimate of adaptation finance funds that may be needed, or on a regional or local scale often limited to a specific vulnerable economic sector. The latter is used to help with budgeting or to support adaptation decisions (to discern the best allocation of effort and funds among adaptation activities). While the methods vary widely between the global scale analysis and regional or sectoral focus, there are important common methodological considerations.

Historical weather data are usually not detailed enough (Hughes et al., 2010); others studies note that data on costs of adaptation actions are sparse. Determining appropriate adaptation actions requires detailed geographic understanding of localized impacts of climate change and this is where climate models confront the greatest uncertainties (Refsgaard et al., 2013). Local and regional-scale adaptation costs are not consistent with global estimates and this is because the latter are not grounded in local-scale physical attributes that are critical for adaptation (Agrawala and Fankhauser, 2008).

The few global and regional adaptation cost assessments over the last few years refer to developing countries and they exhibit a wide range of estimates (Oxfam, 2007, Stern, 2007, UNDP, 2007, UNFCCC, 2008, World Bank, 2010a). Global adaptation costs in the latest and most comprehensive estimate range from US$ 70 billion to more than US$ 100 billion annually by the year 2050 (World Bank, 2010a). There are many practical challenges to conducting global adaptation cost studies (Parry et al., 2009a). In addition, their broad scope limits the analysis to a few climate scenarios and a limited range of adaptation options, co-benefits, equity issues and adaptation decision making.

6.4.2 Sectoral

Support of adaptation decision making at the sectoral level usually relies on studies that follow an econometric or simulation approach. Econometric studies examine observed responses of agents to climate or weather. The simulation approach models a number of components in the chain of impacts starting from climate change, the impacts on the biophysical attributes of interest, e.g., precipitation and temperature, and the behavioral-economic component. The behavioral-economic component may incorporate rational responses by actors or a decision-rule type response to climate stressors. Simulation modeling requires extensive data inputs and calibration. Its advantage is that it can provide appraisal of how specific adaptation strategies at various intensities can affect outcomes, such as finding the change in crop output and water supply resulting from water resource management techniques used to respond to climate change.

Chambwera et al. (2014) identify a number of desirable characteristics that derive from the many studies attempting to evaluate adaptation options. Together they provide a broad representation of climate stressors, a wide variety of alternative adaptation responses, rigorous economic analysis of costs and benefits (including market, non-market and socially-contingent implications), and a strong focus on adaptation decision making with a clear exposition of the form of adaptation decision making implied by the study. Chambwera et al. (2014) provide an overview of sectoral adaptation studies, the methodology used and the key points illustrated (see Table 6.1).

Table 6.1. Adaptation strategies

Sector	Study and scope	Methodology	Key points illustrated
Agriculture, forestry, and livestock	Seo and coinvestigators (e.g., Seo et al., 2008b, 2009b, 2011): Impacts to livestock producers in Africa	Econometric. Examines the economic choices that livestock owners make to maintain production in the face of climate. Insights into adaption possibilities are achieved by examining the ways economic choices vary over locations and times with varying climate conditions.	• Consideration of multiple options (implicit) • Residual impacts reflected • Applicable at multiple geographic scales • Results provide a ready means to re-estimate results for multiple climate scenarios.
	Butt et al. (2006): Crop sector in Mali	Simulation. Simulates the economic implications of potential adaptation possibilities. Examines the consequences of migration in cropping patterns, development of heat resistant cultivars, reduction in soil productivity loss, cropland expansion, and changes in trade patterns.	• Broad consideration of options (explicit, allowing for ranking of measures) • Residual impacts reflected • Rigorous economic costing of adaptation options and consequences for yields, revenue, and food security
	Sutton et al. (2013): Crop and livestock sector in four eastern European and central Asian countries	Simulation with benefit /cost analysis. Ranks options initially based on net economic benefits over 2010 – 2050 period. Considers non-market and socially contingent effects through stakeholder consultation process.	• Broad consideration of options (explicit, measures ranked) • Very broad representation of climate scenarios (56 GCM–Special Report on Emission Scenarios combinations) • Rigorous economic costing of adaptation options • Integrated analysis of agriculture and irrigation water sectors
Sea level rise and coastal systems	Nichols and Tol (2006): Coastal regions at a global scale	Simulation of adaptation through construction of seawalls and levees, adoption of beach nourishment to maintain recreational value, and migration of coastal dwellers from vulnerable areas. The study reflects an economic decision rule for most categories and benefit /cost analysis for a few categories	• Capable of broad representation of sea level rise scenarios • Optimization of alternatives considering impact of adaptation and resulting residual impacts • Rigorous economic costing of adaptation options
	Neumann et al. (2010a): Risks of sea level rise for a portion of the coastal United States	Simulation of adaptation decision making including seawalls, bulkheads, elevation of structures, beach nourishment, and strategic retreat, primarily using a benefit /cost framework but with alternatives based on local land use decision-making rules	• Capable of broad representation of sea level rise scenarios • Flexibility to consider both benefit /cost and rule-based decision making • Rigorous and dynamic economic costing of adaptation options
	Purvis et al. (2008): Risks of	Simulation using a probabilistic representation to characterize	• Considers the impact of both gradual climate change

Sector	Study and scope	Methodology	Key points illustrated
	coastal flooding in Somerset, England	uncertainty in future sea level rise and, potentially, other factors that could affect coastal land use planning and development investment decisions	(sea level rise) and extreme events (1-in-200-year recurrence interval coastal flooding event) • Incorporates probabilistic uncertainty analysis
Water	Ward et al. (2010): Future needs and costs for municipal water across the world, scalable to national and local scales	Assesses costs with and without climate change of reaching a water supply target in 2050. Aggregation level is food producing units, and storage capacity change, using the secant peak algorithm to determine the storage yield relationship and the cost of various alternative sources of water. Authors find that baseline costs exceed adaptation costs ($73 vs $12 billion/ year for adaptation), with 83 – 90% of adaptation costs incurred in developing countries.	• Multiple climate scenarios • Scalable to multiple spatial resolutions, with national and regional results reported • Multiple alternative adaptation options considered • Rigorous economic costing of site-specific capital and operating costs
Urban flooding	Ranger et al. (2011): direct and indirect impacts of flooding in Mumbai, India	Investigates the consequences of floods with different return periods, with and without climate change; the effect of climate change is from a weather generator that downscales simulations from a global climate model. Estimates direct losses from a 100-year event rising from $600 million today to $1890 million in the 2080s, and total losses (including indirect losses) rising from $700 to $2435 million. Impacts give rise to adaptation options, some targeting direct losses (e.g., improved building quality) and others targeting indirect losses (e.g., increased reconstruction capacity). Analysis finds that improved housing quality and drainage could bring total losses in the 2080s below current levels and that full access to insurance would halve indirect losses for large events.	• Considers multiple adaptation options • Explicitly considers both direct and indirect costs • Rigorous economic costing of adaptation options
Energy	Lucena et al. (2010): Energy production in Brazil, particularly from hydropower	Simulation of multiple adaptation options, including energy source substitution and regional "wheeling" of power coupled with modeling of river flow and hydropower production under future climatic conditions. Uses an optimization model of overall energy production.	• Considers two GHG emissions scenarios and a "no-climate change" baseline • Scalable to multiple spatial resolutions, with national and regional results • Considers multiple adaptation strategies • Rigorous economic costing

Sector	Study and scope	Methodology	Key points illustrated
			of capital and recurring adaptation costs
Health	Ebi (2008): Global adaptation costs of treatment of diarrheal diseases, malnutrition, and malaria	The costs of three diseases were estimated in 2030 for three climate scenarios using (1) the current numbers of cases; (2) the projected relative risks of these diseases in 2030; and (3) current treatment costs. The analysis assumed that the costs of treatment would remain constant. There was limited consideration of socioeconomic development.	• Multiple climate scenarios • Clear description of framework and key assumptions • Rigorous economic costing of adaptation options using multiple assumptions to characterize uncertainty
Macroeconomic analysis	De Bruin et al. (2009b): Adaptation strategies compared to mitigation strategies within the context of a global IAM	Use of an IAM (the DICE model) with refined adaptation functions. Examines the efficacy of "stock" adaptations (mainly infrastructure) adaptations versus "flow" adaptations (mainly operational or market responses), with comparisons to mitigation investments.	• Multiple climate scenarios • Clear description of framework and key assumptions • Considers multiple adaptation strategies • Rigorous economic costing of adaptation options
	Margulis et al. (2011): Climate change impacts in the economy	Use of a general equilibrium model to simulate two climate change-free scenarios regarding the future of Brazil's economy. Climate shocks were projected and captured by the model through impacts on the agricultural / livestock and energy sectors. The socioeconomic trends of the scenarios with and without global climate change were reviewed in terms of benefits and costs for Brazil and its regions.	• The economic impacts of climate change are experienced across business sectors, regions, states, and large cities and expressed in terms of GDP losses. • The simulation disaggregates results for up to 55 sectors and 110 products and also provides macroeconomic projections such as inflation, exchange rate, household sector consumption, etc. It also includes expert projections and scenarios on specific preferences, technology, and sector policies.

Source: Chambwera et al., 2014, pp. 962-963.

Energy

Evidence of household adaptation to climate factors has shown that demand for energy and associated products (e.g., space heating and air conditioning) fluctuates across climate zones and over the season (Eskeland and Mideksa, 2010, Auffhammer and Aroonruengsawat, 2011, Auffhammer and Mansur, 2014). The adaption benefits in terms of mortality and well-being have been found to be substantial (Deschênes and Greenstone, 2011, Barreca et al., 2013), even when these can be very costly (Barreca et al., 2015). Investments are sensitive to climate and weather change at both the intensive margin (Mideksa and Kallbekken, 2010, Deschênes and Greenstone, 2011) and at the extensive margin, especially with cooling (Mansur et al., 2008).

Other likely adaptations in the energy sector include: power plants may need to build cooling towers; water withdrawals above hydroelectric dams will need to be lowered, in order to allow for increased electricity use; and windmill grids will have to adapt to new wind patterns (Pryor and Barthelmie, 2010).

In terms of public adaptation options for Europe, episodic disruptions related to extreme weather events currently present the major risk for supply and use of energy. Current and future energy systems should be climate proofed. Given the significant effects of climate change on potential power for many renewable energy sources, an important role for adaptation is to take account of these in siting and design decisions. Measures should be considered for increasing supply and peak load supply of energy for cooling in areas likely to confront higher average temperature and temperature extremes (Ansuategi, 2014).

Health

The studies on household adaptation to climate change through demand for energy and associated products have shown one important form of private adaptation that protects health. Beyond this focus on the energy sector in developed economies, a lot of research has suggested potentially severe impacts of climate change on mortality and morbidity (Cline, 1992, Fankhauser, 1995b) but surprisingly little work has been done on health adaptation (Massetti and Mendelsohn, 2015). Adaptation strategies could include early warning systems for extreme events, control of vector populations (spraying insecticide on mosquitoes), encouraging protective clothing, immunizations and medical treatment.

In studies on costs and benefits of adaptation, there is limited coverage of the health sector and most of it is focused on costs (Parry et al., 2009b, Hutton, 2011, Watkiss and Hunt, 2011, Chiabai and Spadaro, 2014).

Tourism

Some evidence in tourism has shown that holiday makers change destinations (Hamilton et al., 2005), dates of travel (Amelung and Moreno, 2012), or the nature of their vacation, for example, beaches to mountains (Bigano et al., 2006), to account for climate variables. Outdoor recreation that depends on warm weather will grow, while winter recreation will shrink. Overall recreation is likely to expand, given the predominance of warm weather recreation, and the tourism and sports industries will adapt to exploit new opportunities (Massetti and Mendelsohn, 2015).

Agriculture

In terms of private adaptation, agriculture has been the most studied sector. Different climate conditions give rise to differences in agricultural practices such as crop choice and animal husbandry (Rosenzweig and Tubiello, 2007, Seo and Mendelsohn, 2008a, 2008b, 2008c, Lotze-Campen and Schellnhuber, 2009, Seo et al., 2009a, Nhemachena et al., 2010, Auffhammer and Schlenker, 2014). Short-term weather fluctuations also lead to adjustments in the size of farms or prompt a move to non-farm activities (Kazianga and Udry, 2006, Banerjee, 2007, Mueller and Quisumbing, 2011, Eskander and Barbier, 2016). Di Falco and Veronesi (2013) found that such farm adaptation strategies can be highly beneficial when the right combination of measures is taken. Moore and Lobell (2014) find adaptation potential for many crops in Europe.

Drawing on an overview of adaptation research in agriculture, Massetti and Mendelsohn (2015) find that without adaptation there are large potential risks, but that by changing patterns in trade in response to climate change, along with farm level adaptation and carbon fertilization, total global food production will remain robust for this century barring extreme scenarios.

For Europe, studies show that climate change will bring both desirable and undesirable consequences for agriculture. Farmers can be supported through research and advisory services to help inform adaptation aimed at tackling risks and exploiting opportunities, e.g., biotechnology breakthroughs in developing crop and livestock varieties that are resilient or more productive with climate change. Financially safeguarding farmers from risk to agricultural income is likely to become an important adaptation option, while technical adaptation options for agriculture in the face of extreme climates seem limited (Nainggolan et al., 2014).

Migration

Another important way in which households adapt to climate factors is through emigration. Weather shocks or worsening climate conditions have been shown to lead to emigration (Smith et al., 2006, Feng et al., 2010, Boustan et al., 2012, Henderson et al., 2014). A number of recent surveys (Millock, 2015, Waldinger, 2015, Waldinger and Fankhauser, 2015) show that, overall, recent empirical local studies confirm that environmental change induces migration. Beine and Parsons (2015) show no significant impact of temperature or rainfall deviations on international migration, although they explicitly focus on direct effects of climatic events rather than indirect effects such as the impact on wages. In contrast, Cattaneo and Peri (2016) focus on total effects and find significant emigration effects in middle- and lower-income countries. It is worth noting that what in many contexts may be an important private adaptation strategy with important potential benefits can also become a new source of substantial welfare costs when, for instance, migration leads to conflict and threatens livelihoods. This suggests limits to adaptive capacity. Fankhauser (2017) distinguishes between planned, proactive migration and reactive relocation in an emergency, which is a sign of adaptation failure.

Coasts

Valuable coastlines can be protected from sea level rise but this can be costly. Yohe et al. (1995) and Fankhauser (1995c) provide early studies comparing the benefits of protected assets against the costs of sea defenses, while there are a number of more recent and refined studies (Bosello et al., 2007, Vafeidis et al., 2008, Hinkel and Klein, 2009). Economic studies and dynamic programming help to determine the timing of coastal protection and retreat and show that there are great benefits from protecting developed land (Yohe et al., 1996, Hallegatte et al., 2013).

A very limited number of approaches have been applied to assessment of costs of climate change impacts and adaptation to coastal areas, with important differences in cost estimates that depend on the approach and input data used. Sea level rise has been the major source of impact considered, but most studies do not consider the regional sea level rise that is needed for proper estimation of inundation damage. Only a small range of adaptation options have been considered in those models that do assess its role (Nainggolan et al., 2014).

Extreme events

Due to the nature of extreme events (their rareness), it is difficult to adapt to them. Reactive adaptation includes early warning systems, emergency relief and mandatory evacuations. If the events are frequent enough, expected benefits may warrant engineering solutions such as building sea walls against tropical storms, structures against winds, and levees for floods. Emergency shelters and early warning systems can help protect against heat waves, although cooling may be the most effective adaptation (Deschênes and Greenstone, 2011). As insurance reflects potential dangers, it can incentivize adaptation to extreme events. For the same reason, disaster relief and subsidized insurance can give the wrong signal and lead to maladaptation by encouraging risk taking.

Forestry

Changes in forest growth, fire risk and regeneration are predicted changes in ecosystem models. Adaptation of forest can be undertaken by managers with dynamic strategies that gradually alter the stock over time and by changing the harvesting, planting and management intensity (Massetti and Mendelsohn, 2015). Such adaptation can reduce the fire risk and move forests toward more productive locations (Sohngen and Mendelsohn, 1998).

Water

Climate change can lead to reductions in water flow with substantial loss to welfare when the affected water loss is to high-valued municipal or industrial uses (Cline, 1992). Adaptations for the water sector include: the use of dams to mitigate interannual and seasonal water fluctuations; use of canals and water ducts to move water to cities; desalinization plants; water treatment plants; and water saving appliances.

Relocation of water from low- to high-valued uses is another form of adaptation. If water were subject to the market mechanism, this would be the result of private adaptation. In general, water is not traded but is allocated by rights and regulations (Wahl, 1989, Griffin, 2012) and in ways that do not equate marginal value across uses, suggesting substantial losses resulting from reduced supply (Howitt and Pienaar, 2006).

Reallocation of water requires difficult institutional change in the form of defining property rights and facilitating trade across users (Olmstead, 2014).

Business community

Adaptation behavior in the business sector has received surprisingly little attention in the peer-reviewed literature (Linnenluecke et al., 2013). Agrawala et al. (2011c) provide a good summary of available evidence and find that many firms are aware of future climate change and most firms manage current climate risks. Rather than consciously engaging in adaptation, climate risks may be addressed through business continuity planning and supply chain management (see also Biagini and Miller, 2013).

For the business community, climate change can also be seen as an opportunity. A firm could have a comparative advantage by having a climate-resilient supply chain. Many new products and services will arise from the need to adapt, such as water-efficient appliances, risk-management services or urban drainage solutions. There is evidence, for instance, of innovation in risk mitigation and water-saving technology (Biagini and Miller, 2013, Miao and Popp, 2014).

6.5 Climate adaptation policy instruments

This section presents the policy tools and instruments for adaptation. There are many ways for the authorities to provide the appropriate incentives for private adaptation. Economic instruments are meant to affect behavior of those that have most to gain, thus providing incentives if preferred in general to regulation that is less flexible in allowing different levels of private action. There is relatively little literature on the use of economic instruments for adaptation, with insurance and trade-related instruments being the exception.

Economists tend to prefer flexible instruments that provide incentives to economic agents to undertake action when it is in their interest, rather than mandates or uniform policies. The main reason for this is that these policies are more likely to be cost effective as they allow adaptation effort to be undertaken by those that can better afford to adjust. Another reason is that the authorities usually do not have the requisite information to determine how best adaptation effort should be allocated. Insurance markets, water markets and payments for environmental service (PES) schemes are examples of flexible economic instruments for adaptation.

Poorly designed policies can lead to perverse outcomes. Subsidizing irrigation water has been found to lead farmers to increase total water use by extending the acreage under irrigation (Pfeiffer and Lin, 2010). Likewise, increases in the efficiency of resource use can lead to a rebound effect resulting in increased demand for the resource in question (Roy, 2000).

While the potential for the use of economic instruments to promote adaptation is widely recognized, there is a paucity of literature on this topic. Four classes of incentive-providing instruments have been identified (Agrawala and Fankhauser, 2008, Chambwera et al., 2014). These are: (1) insurance schemes for extreme events, (2) price signals/markets for water and ecosystems, (3) regulatory measures and incentives such as building standards and zone planning, and (4) research and development incentives for agriculture and health.

Insurance, microinsurance, reinsurance and risk pooling arrangements are formal mechanisms that can provide incentives for adaptation. Indemnity-based insurance provides coverage and post-event claim payments in return for ongoing premium payments. Index-based insurance, in contrast, does not insure the loss but rather an event (such as the measured loss of rainfall). It has the advantage of avoiding moral hazard but may suffer from the lack of correlation of loss to event (Collier et al., 2009, Hochrainer et al., 2009). There are substantial differences in how liability and responsibility are distributed in different insurance markets (Botzen et al., 2009, Aakre et al., 2010). Governments often play a central role as regulators, insurers or reinsurers (Linnerooth-Bayer et al., 2011).

In addition to formal insurance mechanisms, there are also informal mechanisms that include national or international reliance on aid or remittances, although they tend to break down for large, covariate events (Cohen and Sebstad, 2005). The inclusion of climate change risk under corporate disclosure regulations is also an informal mechanism. Insurance mechanisms can in general promote adaptation by reducing follow-on risk and consequences after an event, or by improving decisions and reducing risks prior to an event (Hess and Syroka, 2005, Hoeppe and Gurenko, 2006, Skees et al., 2008). One way in which adaptation is incentivized is that agents may take action to reduce risks associated with climate change in order to reduce insurance premiums, although this incentive effect has been found to be weak (Kunreuther et al., 2013b). Insurance, however, can also lead to moral hazard in that it can lead to reducing risk-minimizing efforts given coverage (Kunreuther and Roth, 1998). Some current insurance schemes may lead to maladaptation, such as when people feel covered when they build in disaster-prone areas (Rao and Hess, 2009). Another example is the under-insurance which may result if agents expect the government to provide disaster assistance (Gibson et al., 2008, Raschky et al., 2013).

Payments to economic agents to undertake adaptation and mitigation activity or to preserve the health of the environment and public health are classified as payments for environmental services. There is some recent evidence of adaptation-focused PES schemes of a pilot nature (Bräuninger et al., 2011, Schultz, 2012, van de Sand, 2012). There are also potential synergies between PES schemes and community-based adaptation (Chishakwe et al., 2012).

Water markets or water-pricing schemes have been suggested as a means of resolving water allocation conflicts arising from water shortage (Vörösmarty et al., 2000, Adler, 2008, Alavian et al., 2009). Besides helping the transfer from lower to higher valued uses (Olmstead, 2010), urban fees and real estate taxes can influence water allocation decisions. Medellín-Azuara et al. (2008) make the case that water markets improve climate change adaptation. Important institutional barriers to water markets and pricing remain in many countries in the form of inadequate property rights, limits on transferability, and legal and physical infrastructures (Saleth and Dinar, 2004, Turral et al., 2005, Griffin, 2012).

Market-based instruments in the form of taxes, subsidies and tradable permits have played a prominent role in the debate about ways to mitigate climate change. Their potential use for adaptation policy has not been discussed as much. The use of pricing mechanisms for water management, or the strengthening of property rights to help make PES mechanisms more effective, are perhaps the exception.

An instrument for adaptation that is increasingly viewed as important is technology transfer. Christiansen et al. (2011) provide a list of technological needs of developing countries related to mitigation and adaptation. Patents and intellectual property protection have often constrained the transfer of knowledge and can potentially limit adaptation (Henry and Stiglitz, 2010) but a number of measures have been used to relax these constraints (Dutz and Sharma, 2012). International financial institutions and foundations can buy out a patent and acquire the market rights for a patented product in a developing country. A group of patent holders can also agree to license their individual patents to each other (patent pools). In some cases, governments allow patent rights to be overridden.

Adaptation investments can be encouraged through subsidies for innovation through research and development (Bräuninger et al., 2011). While they are popular with the wider public and public authorities, subsidies can be liable to rent seeking and adverse effects on competitiveness (Barbier and Markandya, 2013). There is no evidence of their use for climate adaptation.

The growing interest in behavioral and experimental economics has suggested that the effectiveness of incentive mechanisms will largely depend on how people actually behave. If behavior is characterized by bounded rationality, individuals may overestimate or underestimate risks (Kahneman and Tversky, 1979, Ellsberg, 2001), or they may be inconsistent in making choices over time (Ainslie, 1975). By taking into account such behavioral biases, incentive policies may be more effective. The way in which the public is informed, for instance, can have an important impact on its response. Information that is abstract or refers to distant events does not draw attention as compared to concrete, current and emotionally-charged information (Trope and Liberman, 2003).

6.5.1 Climate adaptation finance

Climate adaptation finance is a subset of the broader category of climate finance that refers to financial flows that aim at "reducing emissions, and enhancing sinks of GHGs and aim at reducing vulnerability of, and maintaining and increasing resilience of, human and ecological systems to negative climate change impacts" (UNFCCC, 2014, p. 5). The Paris Agreement extends previous commitments on finance but provides few specifics. Advanced economies are strongly urged to ramp up their efforts to achieve the goal of providing US$ 100 billion a year in finance to support adaptation and mitigation to developing countries by 2020. Starting from a floor of US$ 100 billion, the parties of the Paris Agreement are expected to set a new, quantified yearly goal. This commitment is viewed as a prerequisite for developing countries moving on mitigation pledges (Farid et al., 2016).

Beyond commitments made by the international community toward the developing economies, adaptation finance includes financial flows from the private and public sector associated with mitigation and adaptation. Overall climate finance flows in 2014 were estimated to range from US$ 340 to 650 billion (UNFCCC, 2014). The range illustrates the difficulty of estimating climate finance flows. Adaptation finance reached US$ 25 billion and accounted for 15 percent of overall climate finance flows in 2014, with the proportion in developed economies being smaller (Buchner et al., 2014, Buchner et al., 2015).

The literature on climate finance has generally focused more on issues pertaining to a low-carbon transition than to financing adaptation. When it comes to climate adaptation finance, there is a substantial literature on the question regarding the international financing of adaptation of the developing economies or the support of climate-resilient development. This has given rise to both an interest in effective adaptation strategies and in the best ways to finance them. Accordingly, studies have looked at ways of costing adaptation at the global, regional, national, local and sectoral levels, with an eye toward 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 the context of the responsibility toward developing countries) is meant to provide assistance over and above the traditional development assistance, but this raises numerous analytical complications.

Overall, there has been much less focus on the question of national adaptation finance for developed economies. Some of the issues raised in the literature on adaptation assistance to developing economies may have relevance to this issue, e.g., raising adaptation finance and allocating it among competing needs. Moreover, when considering national adaptation finance for developed economies, this can be seen as an important instrument within the broader set of policy instruments for adaptation policy and as being closely linked to climate insurance.

6.6 References

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7 Building Blocks of Climate–Economy Models

7.1 The discounting process

Discounting refers to the process of assigning a lower weight, i.e., importance, to a unit of benefit or cost in the future than to that unit in the present time. The further into the future the benefit or cost occurs, the lower the weight attached to it. When long-term projects are evaluated – note that the vast majority of environmental, and especially climate-change-related, projects are long-term – the weights refer to the benefits and costs associated with future generations. This creates a moral dilemma.

Let the weight that is attached to a gain or loss in any future year, t, be w_t. Discounting implies that $w_t < 1$. Moreover, discounting implies that the weight associated with benefits or costs occurring in year $t + j$, $j > 1$, should be lower than the weight associated with year $t + j - 1$.

The discounting formula, with a constant discount rate r, is:

$$w_t = \frac{1}{(1+r)^t} \quad , \quad \text{discrete time}$$

$$w(t) = \mathrm{e}^{-rt} \quad , \quad \text{continuous time.}$$

In this formula, w_t or $w(t)$ is called the **discount factor**.

If $r = 0.04$, then $w_{20} = 0.456$. This means that a gain or loss 20 years from now, $t = 0$, would be valued at only 45.6% of its value if it had occurred now. For the same discount rate of 4%, an environmental damage 40 years from now would be valued at 20.8% of its value now, since $w_{40} = 0.208$. For a discount rate of $r = 0.01$, the corresponding weights are $w_{20} = 0.818$, $w_{40} = 0.672$. In Figure 7.1, the present value of €1 at different discount rates is presented.

It is clear that costs and benefits accruing in the distant future have a very small present value if the discount rate is high. These values illustrate what David Pearce referred to as the 'tyranny of discounting' (Pearce et al., 2006, p. 23). Therefore, if the rate is relatively high, benefits from preventing serious climate change accruing in the distant future to future generations will have a very small present value now. Since the cost of preventing the climate change will occur now, this makes it difficult, using CBA rules, to get acceptance for projects which are designed to prevent the impacts of climate change in the distant future.

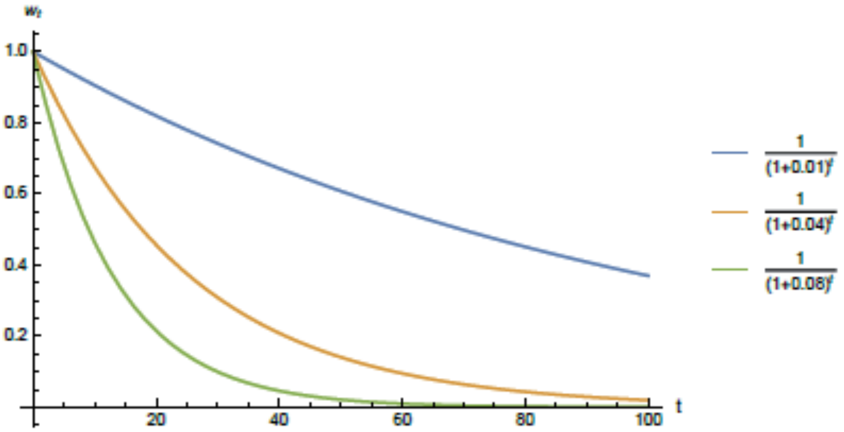

Figure 7.1. Discounting

7.1.1 The social discount rate

In social CBA, a discount rate is the rate of decrease in the social value of public sector income or consumption over time. Two approaches are usually considered when determining social discount rates: the **social time preference** (STP) approach, and the **social opportunity cost** (SOC) approach.

- The STP rate, also referred to as the **social discount rate** (SDR), is the rate of decline in the social value of consumption, as opposed to public sector income. It is also known in the literature as the **consumption rate of interest** (CRI). In this chapter we use the three terms interchangeably, selecting each time the one that best suits the particular use.
- The SOC is usually identified with the real rate of return earned on a marginal project in the private sector.

In CBA, and especially in environmental CBA or climate change CBA, we concentrate on the SDR (CRI).

7.1.2 Determining the social discount rate

The Ramsey rule

The social discount rate can be derived using the so-called Ramsey rule, which states that the discount rate for consumption streams or the CRI is defined as:

$$r = \rho + \eta g,$$

where ρ is the social rate of time preference, or pure time preference – that is, the utility discount rate; η is the elasticity of marginal utility, or the curvature of the utility function; and g is the rate of growth of per capita consumption.

The Ramsey rule for the CRI is derived directly from the Keynes-Ramsey rule determining the rate of growth of consumption along the optimal growth path, that is:

$$\frac{\dot{c}}{c} = \eta(c)\left[f'(k) - \rho - \delta\right],\ \eta(c) = -\frac{u'(c)}{u''(c)c}$$

$$u(c) = \frac{c^{1-\eta}}{1-\eta} \Rightarrow \eta(c) = \frac{1}{\eta},\ u(c) = \ln c \Rightarrow \eta(c) = 1,$$

where $f'(k)$ is the marginal product of capital, δ the depreciation rate and $\eta(c)$ the elasticity of marginal utility of consumption. In a market economy, firms maximize profits and set the marginal product of capital equal to the user cost of capital, i.e., $f'(k) = r + \delta$, where r denotes the market rate of interest. With $\eta(c) = \frac{1}{\eta}$, the Keynes-Ramsey rule implies

$$\frac{\dot{c}}{c} = \frac{1}{\eta}(r - \rho) \Rightarrow r = \rho + \eta g$$

$$g = \frac{\dot{c}}{c}.$$

Arbitrage arguments

The SDR can also be derived from arbitrage arguments. In this context, the consumption discount rate can be defined by the equilibrium condition in two equivalent ways: (i) following Arrow et al. (2012, 2014) and considering a social planner who would be indifferent between \$1 received at time t and \$$\varepsilon$ received today when the marginal utility of \$$\varepsilon$ today equals the marginal utility of \$1 at time t, or (ii) following Gollier (2007) and considering a marginal investment in a zero coupon bond which leaves the marginal utility of the representative agent unchanged.

Assuming that the utility function of the representative agent depends on consumption,

$$U = u(c(t)),$$

the equilibrium condition associated with the Arrow et al. (2014) approach implies that

$$\varepsilon u'\left(c\left(0\right)\right) = \mathrm{e}^{-\rho t} u'\left(c\left(t\right)\right), \text{ or}$$

$$\varepsilon = \frac{\mathrm{e}^{-\rho t} u'\left(c\left(t\right)\right)}{u'\left(c\left(0\right)\right)} = \mathrm{e}^{-r_t t}, \tag{7.1}$$

where r_t denotes the annual consumption discount rate between periods 0 and t and ρ is the utility discount rate. The equilibrium condition associated with the Gollier (2007) approach implies that

$$u'\left(c\left(0\right)\right) = \mathrm{e}^{-\rho t} u'\left(c\left(t\right)\right)\mathrm{e}^{r_t t}, \tag{7.2}$$

where r_t is interpreted as per period rate of return at date 0 for a zero coupon bond maturing at date t. Both approaches are equivalent for determining the consumption discount rate. Assume, as is common in this literature, a constant relative risk aversion utility function,

$$u\left(c\left(t\right)\right) = \frac{1}{1-\eta}\left[c\left(t\right)\right]^{1-\eta}, \ 0 < \eta < \infty,$$

where η is both the coefficient of relative risk aversion and (minus) the elasticity of marginal utility with respect to consumption. Then, taking logs in (7.1) or (7.2), we obtain

$$r_t = \rho - \frac{1}{t}\ln\frac{u'\left(c\left(t\right)\right)}{u'\left(c\left(0\right)\right)} = \rho - \left(-\eta\right)\frac{d\ln c\left(t\right)}{dt} \Rightarrow$$

$$r_t = \rho + \eta g\left(t\right),$$

where $g\left(t\right) = \dot{c}\left(t\right)/c\left(t\right)$ is the consumption rate of growth. Thus $\rho + \eta g\left(t\right)$ is the standard Ramsey-rule discount rate. The SDR depends on the values of three parameters: $\eta, \rho,$ and g.

Calculating the social discount rate

The pure rate of time preference, ρ, measures the extent to which future utility is discounted. A higher value for ρ implies less weight being put on the welfare of future generations, which means less weight on future damages and hence less abatement today. The major difference between the utility discount rate in the *Stern Review* (Stern, 2007), which is $\rho = 0.1\%$ per year, and that in most other cost-benefit analyses of climate change, is that Stern uses a very low pure rate of time preference. This implies that he takes a very egalitarian view of intergenerational distribution. In fact, the only reason why Stern gives a value of ρ that differs from zero is the risk that future generations might not be around at all. Alternative values of ρ which have been used in various studies include: 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 is the index of the aversion society ought to display toward consumption inequality among people – whether they are people in the same period or in different periods (Dasgupta, 2008). Regarding the value of η, Mehra and Prescott (1985) suggest that a value above 10 is not justifiable, while Dasgupta (2008) suggests that values of η in the region of 1.5 to 3 would be reasonable.

The higher the value of η, the less we care for a dollar more of consumption as we become richer. Since we expect that we will be richer in the future when climate damages will be felt, a higher η also implies that damages will be valued lower. Thus, a higher value of η implies less GHG abatement today, unless for some reason we will be poorer rather than richer in the future. In this case, a higher η would give higher damage values, which would justify more abatement today (Sterner and Persson, 2008).

Table 7.1. Indicative SDR values for selected European Union countries, based on the social time preference (STP) rate approach

Non CF countries	g	η	ρ	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	η	ρ	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

Note: CF = Cohesion Fund.

Source: European Commission, 2008, *Guide to Cost Benefit Analysis of Investment Projects: Structural Funds, Cohesion Fund and Instrument for Pre-Accession*, Table B2.

Alternative values of η which have been used in various studies include: Cline $\eta = 1.5$; Nordhaus (1994) $\eta = 1$; DICE (2007) $\eta = 2$; RICE (2011) $\eta = 1.5$; Stern $\eta = 1$. Using $g = 1.3\%$ per year, the following estimates of the SDR (or CRI) are obtained: r (Cline) = 2.05%, r (Nordhaus 1994) = 4.3%, r (Stern) = 1.4%.

Indicative SDR values used in selected EU countries are presented in Table 7.1.

The social discount rate under risk

When future consumption is uncertain, the SDR formula becomes

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

where $\mathbb{E}$ denotes expected value. If we expect to consume more in the future, that is, $\mathbb{E}c\left(t\right) > c(0)$, the marginal utility of one more euro in the future is smaller than the marginal utility of one more euro immediately: $U'\left(\mathbb{E}c\left(t\right)\right) < U'\left(c(0)\right)$. This implies that

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

is positive. This positive wealth effect is increasing in the expected growth rate of consumption over the entire period $[0,t]$ and in the rate at which marginal utility is decreasing with consumption, which is measured by the index of relative risk aversion η. The intuition is that higher expectations about future incomes reduce the willingness to save, thereby raising the equilibrium interest rate.

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 in the underlying probability space $\left(\Omega, \mathcal{F}, \mathbb{P}\right)$ and μ, σ are two scalars measuring respectively the mean and standard deviation of the change in log consumption, then the Ramsey formula becomes (Gollier, 2007):

$$r_t = \rho + \eta\mu - \frac{1}{2}\eta^2\sigma^2. \tag{7.3}$$

The last term in (7.3) is a precautionary effect: uncertainty about the rate of growth in consumption reduces the discount rate, causing more savings in the present. The magnitude of the precautionary effect is, however, likely to be small, at least for the United States. Using annual data from 1889-1978 for the US, Kocherlakota (1996) estimated μ to be 1.8% and σ to be 3.6%. This implies that the precautionary effect is 0.26%.

7.2 Climate change adjustments and the Ramsey rule

Consider the simplified Ramsey problem with climate change, in which the social planner solves:

$$\max_{c,E} \int_0^\infty e^{-\rho t} u(c,T)\,dt,\ u(c,T) = \frac{\left(Ce^{-\gamma T}\right)^{1-\eta}}{1-\eta}, \gamma > 0, \eta \geq 1$$

subject to

$$\dot{k} = F(k,E) - c - \zeta E - \delta k, k(0) = k_0\ , F(k,E) = Ak^\alpha E^{1-\alpha}$$
$$\dot{T} = \Lambda E - mT, T(0) = 0,$$

where, as usual, c is consumption, k capital stock, E fossil fuel energy input, T global average temperature, ζ fossil fuel cost, Λ the impact of fossil fuel emission on temperature and $m \geq 0$ temperature 'depreciation' due to outgoing radiation as temperature increases. When $m = 0$, temperature dynamics follow the proportionality relationship between temperature change and cumulative emissions introduced by Matthews et al. (2009) and Matthews et al. (2012). The current value Hamiltonian for the problem becomes

$$H = u(C,T) + \lambda\left[F(k,E) - C - \zeta E - \delta k\right] + \mu(\Lambda E - mT).$$

The maximum principle implies the following optimality conditions:

$$\frac{\partial H}{\partial C} = u_C(C,T) = \lambda \tag{7.4}$$

$$\frac{\partial H}{\partial E} = F_E(k,E) = \zeta \tag{7.5}$$

$$\dot{\lambda} = \left(\rho + \delta - F_k(k,E)\right)\lambda \tag{7.6}$$

$$\dot{\mu} = (\rho + m)\mu - u_T(C,T)\ . \tag{7.7}$$

Taking the time derivative of (7.4) and using the specification of the utility function, we obtain

$$u_{CC}(C,T)\dot{c} + u_{CT}(C,T)\dot{T} = \dot{\lambda}.$$

Substituting λ and $\dot{\lambda}$ in (7.6), dividing by u_{CC} and using the utility function specification, we obtain

$$\frac{\dot{C}}{C}-\frac{\gamma(\eta-1)}{\eta}\dot{T}=\left(F_k(k,E)-\rho-\delta\right)\frac{1}{\eta}.$$

Using the profit maximizing condition $F_k(k,E)=r+\delta,$ the climate change adjusted discount rate is obtained as:

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

If we adopt the proportionality relationship between temperature change and cumulative emissions, that is $\dot{T}=\Lambda E,$ the SDR becomes

$$r=\rho+\eta\frac{\dot{C}}{C}-\gamma(\eta-1)\Lambda E. \tag{7.8}$$

- The term $\gamma(\eta-1)\dot{T}$ or $\gamma(\eta-1)\Lambda E$ is the climate change adjustment to the Ramsey rule for the discount rate. The sign of the adjustment depends on the value of η for which, as indicated above, values in the region of 1.5 to 3 would be reasonable.
- Thus values of η greater than 1 are plausible, and therefore in such cases climate damage effects cause market discount rates to be smaller than the Ramsey rule.
- Since the effect is larger, the larger are γ and Λ and the emissions path $E(t)$, the plausible assumption that the world will continue increasing emissions before they finally start to decrease (see e.g. Pierrehumbert, 2014, Figure 1) implies that the effect of climate change on market discounting in (7.8) could be quite large for η greater than 1.
- The climate change adjustment generates a precautionary effect. Since η also reflects the relative risk aversion, increasing temperatures or high emissions reduce the SDR, causing more savings in the present.

The exact specification of the climate adjustment depends on the specification of the damage function. If

$$U(C,S)=\frac{\left(CS^{-\gamma}\right)^{1-\eta}}{1-\eta},$$

where S is the stock of GHGs, with $\dot{S}=\beta E-\zeta S,\ S(0)=S_0,$ then – following the same approach – the climate adjusted Ramsey rule becomes

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

In this case, it is the rate of growth of GHGs, $\dot{S}/S$, that determines the adjustment.

7.3 Declining discount rates

7.3.1 The expected net present value approach

The SDR based on the Ramsey formula is constant if we approximate the growth rates $(\dot{C}/C,\ \dot{S}/S)$ or the rates of change $\dot{T}$ by their long-run average estimates. However, over the last decades, many arguments have been put forward supporting the idea of declining discount rates (DDRs). According to Weitzman (1998, 2001), even if every individual believes in a constant discount rate, the widespread opinion on what it should be makes the effective social discount rate decline significantly over time. Weitzman proved that computing the expected net present value of a project with an uncertain but constant discount rate is equivalent to computing the net present value (NPV) with a certain but decreasing **certainty-equivalent** discount rate.[23]

Suppose that net benefits at time $t, Z(t)$ are discounted to the present at a constant exponential rate r, so that the present value of net benefits at time t equals

$$Z(t)\mathrm{e}^{-rt}.$$

If the discount rate r is fixed over time but uncertain, then the expected value of net benefits is given by:

$$p(t)Z(t) = \mathbb{E}[\mathrm{e}^{-rt}]Z(t),$$

where $p(t)$ is the expected discount factor. Therefore, the certainty-equivalent discount rate R_t used to discount $Z(t)$ to the present is defined by:

$$\mathrm{e}^{-R_t t} = \mathbb{E}[\mathrm{e}^{-rt}] \text{ which implies that } R_t = -\frac{1}{t}\ln p(t) = -\frac{1}{t}\ln \mathbb{E}[\mathrm{e}^{-rt}].$$

To illustrate, if $r = 1\%$ or 7%, each with a probability of 0.5, the certainty-equivalent discount rate ranges from 3.96% in year 1 to 1.69% in year 100.

$$t = 1 \quad R_1 = 0.0396 \quad = \quad -1 \cdot \ln\left[0.5\mathrm{e}^{-0.01 \cdot 1} + 0.5\mathrm{e}^{-0.07 \cdot 1}\right]$$

$$t = 100 \quad R_{100} = 0.0169 \quad = \quad -\tfrac{1}{100} \cdot \ln\left[0.5\mathrm{e}^{-0.01 \cdot 100} + 0.5\mathrm{e}^{-0.07 \cdot 100}\right]$$

23 For an empirical application, see Hepburn et al. (2009).

- The time path of the certainty-equivalent discount rate is referred to as the **effective term structure.**
- The **instantaneous certainty-equivalent discount rate,** or **forward rate**, is given by the rate of change in the expected discount factor, $-(dp_t / dt) / p_t \equiv F_t$. This is the rate at which benefits in period $t+1$ would be discounted back to period t. The DDRs of the above numerical example are shown in Figure 7.2, where the forward rate F_t is the rate used to discount benefits and costs from year $t+1$ back to year t. The effective term structure R_t gives the rate used to discount benefits and costs from year t back to year 0. The UK government uses a step-declining long-term discount rate, which is 3.5% for the first 30 years, then drops to 3% for years 31-75, then to 2.5% for years 76-125, and eventually drops to 1% after 300 years (HM Treasury, n.d.).

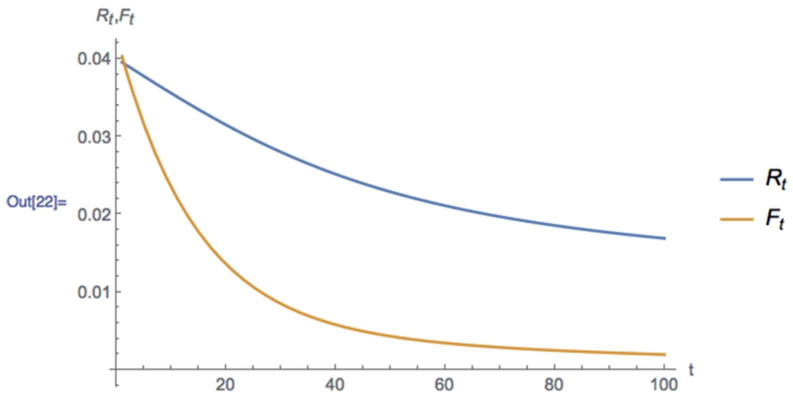

Figure 7.2. Declining discount rates

Once a DDR has been defined, the NPV of a cash flow of net benefits B_t for a project that last T years is defined as:

$$NPV = \sum_{t=1}^{T} R_t B_t .$$

7.4 Gamma discounting

Weitzman (2001) defined time declining discount rates through the so-called **gamma discounting**. Weitzman introduced a frequency distribution of real discount rates based on the opinion of a large number of economists. This distribution suggests the general shape of a gamma probability distribution.

Let

$$A(t) = \int_0^\infty \mathrm{e}^{-xt} f(x)\,dx$$

be the **effective discount function** at time t, which expresses the present value of a euro at time t, weighted by the probability $f(x)$ that the discount rate used for the discounting is the correct one. The instantaneous **effective discount rate** at time t, is then defined as

$$R(t) = \frac{\dot{A}(t)}{A(t)}. \tag{7.9}$$

For the gamma probability distribution,

$$A(t) = \frac{\beta^\alpha}{\Gamma(\alpha)} \int_0^\infty x^{\alpha-1} \mathrm{e}^{-(\beta+t)x} dx,$$

where α, β are positive parameters, with $\mu = \alpha / \beta$, $\sigma^2 = \alpha / \beta^2$ being the mean and the variance of the gamma density function. Then Weitzman (2001) shows that

$$A(t) = \frac{1}{\left(1 + t\sigma^2 / \mu\right)^{\mu^2/\sigma^2}}.$$

Using (7.9), the effective discount rate can be defined as

$$R(t) = \frac{\mu}{1 + t\sigma^2 / \mu}.$$

If $\sigma = 0$, we have the traditional case of a constant discount rate. Using the values of $\mu = 4\%$ per annum and $\sigma = 3\%$ per annum, which are based on a survey of 2160 economists, Weitzman (2001) provides the estimates for a declining discount rate shown in Table 7.2.

A perpetual flow of €1 discounted at a constant discount rate $\bar{r}$ will have a present value of $\int_0^\infty e^{-\bar{r}t} dt = \frac{1}{\bar{r}}$. Therefore an equivalent **as-if-constant** discount rate can be defined as:

$$\frac{1}{\bar{r}} = \int_0^\infty A(t)\,dt \text{ or } \bar{r} = \frac{1}{\int_0^\infty A(t)\,dt},$$

which implies that

$$\bar{r} = \frac{(\mu-\sigma)(\mu+\sigma)}{\mu}.$$

Table 7.2. "Approximate recommended" sliding-scale discount rates

Time period	Name	Marginal discount rate (%)
Within years 1 to 5 hence	*Immediate* future	4
Within years 6 to 25 hence	*Near* future	3
Within years 26 to 75 hence	*Medium* future	2
Within years 76 to 300 hence	*Distant* future	1
Within years more than 300 hence	*Far-distant* future	0

Source: Weitzman, 2001, Table 2.

For $\mu = 4\%$ and $\sigma = 3\%$, $\bar{r} = 1.75\%$. This means that if a constant discount rate has to be used instead of a declining rate, this rate should be less than 2%.

Weitzman (2001), in the context of a Ramsey growth model with an isoelastic or constant relative risk aversion (CRRA) utility function

$$U(C) = \frac{C^{1-\eta}}{1-\eta},$$

derives the gamma discount rate as

$$R(t) = \frac{\left[\left(\frac{\mu}{\sigma}\right)^2 - \eta\right]\ln\left(1 + \frac{\sigma^2}{\mu}t\right)}{t}$$

and the gamma discount factor as

$$A(t) = \left(\frac{1}{1 + \frac{\sigma^2}{\mu}t}\right)^{(\mu/\sigma)^2 - \eta}.$$

In a recent paper, Drupp et al. (2015) point out that the results from Weitzman's survey about the term structure of discount rates depend on whether the responses reflect forecasts of future risk-free interest rates or the ethics of intergenerational equity. If responses reflect forecasts of future risk-free interest rates, then the term structure is flat, implying a nearly constant discount rate. In contrast, if responses reflect ethics of intergenerational equity, then the term structure declines rapidly.

7.5 Modeling climate change damages

7.5.1 The damage function

In climate change economics, the damage function is a reduced form relationship linking damages to the economy with changes in temperature, which takes the form

$$D_t = D(T_t),$$

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

In general there are two ways of introducing damages into the models of climate change and the economy (Weitzman 2010b):

1. Through the utility function that defines the welfare objective

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

   where C is a measure of consumption.

2. Through a multiplicative term associated with the production function

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

   where $F\left(A, K, L\right)$ is a standard production function indicating potential output. In this case, climate damages reduce potential output.

7.5.2 Specifications: damages in the utility function

Consider the following utility function:

$$U\left(C\right) = \frac{C^{1-\eta}}{1-\eta}, \eta > 1,\ U\left(C\right) = \ln C,\ \eta = 1$$

$$-\eta = CU''\left(C\right)/U'\left(C\right),$$

where $-\eta$ is the elasticity of marginal utility, and η is the curvature of $U\left(C\right)$ and the constant coefficient of CRRA. When climate change damages are introduced, the utility function can take the following specifications:

$$U(C,T) = u(C) - D(T)$$

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

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

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

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

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

where Q is environmental quality, $\gamma > 1$ and σ is the elasticity of substitution between C and Q.

7.5.3 Specifications: damages in the production function

In this case, temperature is linked to potential GDP in a multiplicative way. For example, in the different versions of DICE-RICE, the following damage functions have been used:

RICE-96 $\quad D(T_t) = 1 - \frac{1}{1+\theta_{1,i}\left(\frac{T_t}{3}\right)^{\theta_2}} \; i = 1,\ldots,12$ regions

RICE-99 $\quad D(T_t) = 1 - \frac{1}{1+\theta_{1,i}T_t+\theta_{2,i}T_t^2}$

RICE-2011 $\quad D_t = f_1[T_t] + f_2[SLR_t] + f_3[S_t] \approx \theta_1 T_t + \theta_2 T_t^2$

$$\theta_1 = 0.0018, \; \theta_2 = 0.0023$$

$$\Omega_t = \frac{D_t}{1+D_t}$$

DICE-2013R $\quad D(T_t) = 1 - \frac{1}{1-0.00267T^2} \approx 0.023\left(\frac{T_t}{3}\right)^2.$

Output net of damages is:

$$Y = \left(1 - D(T)\right)F(K,L,A,E).$$

In DICE-2013R (Nordhaus and Sztorc, 2013), the damage function implies that the estimated damages at 3 °C increase (temperature anomaly) are 2.3 percent of potential GDP. Damages as a proportion of GDP under different assumptions about temperature increase in general. As presented in DICE-2013R, for a 4 °C global mean temperature increase, the IPCC (2007) estimates damages ranging from 1 to 5 percent of output. For a 2.5 °C global mean temperature increase, damages – according to various models – range from -1 to 2.5 percent of output. This wide variability makes clear the strong uncertainties associated with the estimation of damages resulting from climate change.

Climate dynamics and damages

The relationships between temperature dynamics, GHGs accumulation and central economic aggregates such as utility or GDP are shown below. In the climate dynamics described by equations (7.10)–(7.13), climate change damages affect input.

$$\dot{T}(t) = \frac{\gamma}{\ln 2} \ln\left(\frac{S}{S_0}\right) + F_{EX} - \delta T(t) \tag{7.10}$$

$$\delta = \xi - \kappa,\ \gamma = \sigma\eta,\ F_{EX}:\ \text{exogenous forcing} \tag{7.11}$$

$$\dot{S}(t) = \beta E(t) - \zeta S(t)\ ,\ S(t) = S_0 \tag{7.12}$$

$$Y = \left(1 - D(T)\right) F(K, L, A, E). \tag{7.13}$$

In the climate dynamics described by equations (7.14)–(7.17), climate change damages affect utility.

$$\dot{T}(t) = \frac{\gamma}{\ln 2} \ln\left(\frac{S}{S_0}\right) + F_{EX} - \delta T(t) \tag{7.14}$$

$$\delta = \xi - \kappa,\ \gamma = \sigma\eta,\ F_{EX}\ :\ \text{exogenous forcing} \tag{7.15}$$

$$\dot{S}(t) = \beta E(t) - \zeta S(t)\ ,\ S(t) = S_0 \tag{7.16}$$

$$U\left(C, D(T)\right) = u\left(C, T\right). \tag{7.17}$$

7.5.4 Damage functions in terms of carbon concentration

A very valuable simplification can be achieved by describing damages directly as a function of the level of atmospheric carbon concentration, rather than as a two-step function describing first how carbon concentration maps into temperature and then applying the damage functions defined above. The reason why this is a simplification is that the direct carbon-damage formulation can be calibrated with a functional form that is very analytically convenient (Hassler et al., 2016b):

$$D(T(S)) \approx 1 - e^{-\gamma(S(t)-S_0)}, \quad \frac{1}{1-D}\frac{\partial D(T(S))}{\partial S} = \gamma.$$

In this formulation, output net of damages is $e^{-\gamma(S(t)-S_0)}Y$ and marginal damages as a share of net-of-damage output become:

$$\frac{1}{1-D}\frac{\partial D(T(S))}{\partial S} = \gamma.$$

Golosov et al. (2014) show that a good approximation to the damages used to derive the damage function in DICE (Nordhaus, 2007) is given by $\gamma = 5.3 \cdot 10^{-5}$.

If damages are associated with utility, we have:

$$U(C,S) = u(C) - D(S)$$

$$U(C,S) = \ln\left(Ce^{-\varphi(S-S_0)}\right) = \ln C - \varphi(S - S_0)$$

$$U(C,T) = \frac{\left(CS^{-\gamma}\right)^{1-\eta}}{1-\eta}.$$

Pindyck (2013a, 2017) criticizes the IAMs and the use of damage functions. Pindyck (2017, p. 101) points 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. As a result, developers of IAMs have little choice but to specify what are essentially arbitrary functional forms and corresponding parameter values.

Pindyck (2013b) suggests that the focus should be on damages related to catastrophic outcomes, that is, economic damages which could be associated with temperature increases larger than 5 °C.

7.6 The effects of climate change on productivity

There is a growing body of literature focusing on the effects of temperature increases on productivity and growth. Dell et al. (2009) introduced the process

$$\frac{d\log y_i(t)}{dt} = g + \gamma\left(T_i(t) - \bar{T}_i\right) + (\gamma + \rho)\bar{T}_i + \varphi\left[\log_* y(t) - \log y_i(t)\right], \; t \geq 0,$$

where $\log y_i(t)$ is the log per capita income in geographic area i at time t, $T_i(t)$ is the temperature in area i at time t, $\bar{T}_i$ is the average temperature level in area i, and $\log_* y(t)$ is the relevant frontier level of income to which the area converges. The parameter γ captures the causative short-run effect of temperature shocks on growth, as would be identified in a panel specification such as Dell et al. (2012, 2014). The parameter ρ captures the degree of adaptation over the long run to average temperature levels, potentially offsetting the short-run temperature effects. The parameter $\varphi \in (0,1)$ captures the rate of convergence. It is assumed that all countries start in antiquity at time zero, with the same level of per capita income, $\log y_i(0) = c$ for all i. Results from a data set including 134 countries (Dell et al., 2008) suggest that in poor countries over the 1950-2003 period, a 1 °Celsius rise in temperature in a given year reduced economic growth in that year by 1.1 percentage points, while the findings in Dell et al. (2009) indicate that each additional 1 °Celsius is associated with a statistically significant reduction of 8.5 percentage points of per capita GDP. Furthermore, use of subnational data shows that the negative cross-sectional relationship between temperature and income exists within countries, as well as across countries.

7.6.1 Productivity impacts

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

$$\Omega(T) = \frac{1}{1 + \pi_1 T + \pi_2 T^2} \tag{7.18}$$

$$Y_t = \Omega(T) A_t F(K_t, L_t), \tag{7.19}$$

where $A_t F(K_t, L_t)$ is potential output in the absence of climate change damages. Standard IAMs use the proportional damage-output relationship (7.19) to estimate the impacts of climate change on the level of output, but not on the long-run growth rate which is captured by the growth of TFP, A_t. Dell et al. (2014) introduce a process linking the evolution of TFP with climate change damages:

$$\log A_t = \log A_{t-1} + D(T) \tag{7.20}$$

$$Y_t = A_t F(K_t, L_t), \tag{7.21}$$

where $D(T)$ is a damage function. The difference between climate change impacts on output levels and TFP is striking.

Dell et al. (2014) consider the impact of a permanent increase in temperature that has a contemporaneous effect of lowering economic output by 1 percent in a given year. If the growth of technology A is exogenous and the damage function exhibits level effects, as in (7.18)–(7.19), then the impact of that increase in temperature extrapolated over 100 years would be to lower GDP by about 1 percent. Alternatively, if the impact was modeled through equations (7.20)–(7.21), so that the growth rate of TFP A was 1 percentage point lower per year, then after 100 years the GDP would be lower by about 63 percent.

Results obtained by using distributed lag models (Dell et al., 2012) suggest that, for poor countries, temperature shocks appear to have long-lasting effects; i.e., the damage function is consistent with (7.20)–(7.21). Hsiang and Jina (2014) find similar long-lasting effects for windstorms. Thus, the effects of high temperatures in poor countries appear to reduce the rate of economic growth as in (7.20)–(7.21), rather than having a one-time output level effect as in (7.18)–(7.19). However channels such as institutions, corruption, civil conflict or labor productivity could plausibly affect productivity growth.

7.7 Risk and uncertainty

7.7.1 Sources of uncertainty

A central issue in the economics of climate change is understanding and dealing with the vast array of uncertainties involved. These uncertainties range from those regarding economic factors such as economic growth rates, population growth, emission intensities, new technologies and their rate of adoption and effectiveness, to those regarding climate itself such as the structure of the carbon cycle, the climate response to external forcing – climate sensitivity – or the impact of increasing temperature on precipitation. The interaction of these uncertainties affects damages, and cascades to the costs and benefits of different policy objectives.

Climate change science and policy have focused largely on projecting the central tendencies of major variables and impacts. While central tendencies are clearly important for a first-level understanding, attention focuses on the uncertainties in the projections. Uncertainties take on great significance because of the possibility of nonlinearities in responses, particularly the potential for triggering thresholds in earth systems, in ecosystems or in economic outcomes.

The focus on uncertainty has taken on increased importance because of the attention given by scientists to tipping elements in the earth system, where climate **tipping points** are defined as points where a small forcing is enough to set off a chain of interactions causing a major change in the behavior of the system (Roe and Baker, 2007). An influential study by Lenton et al. (2008) discussed important tipping elements such as the large ice sheets, large-scale ocean circulation and tropical rain forests.

Melting land ice associated with a potential meltdown of the Greenland and West Antarctica ice sheets might cause serious global sea level rise. It is estimated that the Greenland ice sheet (GIS) holds an equivalent of 7 meters of global sea level rise, and arguments have been put forward suggesting that global warming beyond 2 °C will lead to an irreversible melting of the GIS. Moreover, it has been suggested that the West Antarctica ice sheet (WAIS) holds the potential for up to 3.5 meters of global sea level rise (see Lenton et al., 2008). In the discussion about tipping points, it has been stressed that the time scale of melting of the GIS is much longer than that of the WAIS melting. However, while the Antarctic ice sheet could melt very fast once it gets started, it will take an increase of 5 °C of surface temperature for a serious destabilization. Furthermore, a sustained global warming in the range of 1–5 °C above 1990 temperatures could generate tipping points leading to at least partial deglaciation of the GIS and WAIS, thus implying a significant rise in sea levels. Kriegler et al. (2009) provide estimates of the likelihood of crossing tipping points.

Once these uncertainties are included in the analysis, policies will need to account for the probability that certain emission paths may lead across tipping points. It is important that particular concern should be given to tipping points that have irreversible elements.

7.7.2 Uncertainty and integrated assessment models

The sources of uncertainty in climate change which should be addressed in modeling climate and the economy 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.

Parametric uncertainty is the most often analyzed uncertainty in climate change. Some evidence from the impacts of parametric uncertainty on IAMs is presented in Figure 4 of Gillingham et al. (2015), as follows:

- Within each of the nine panels presented in Figure 4, the *y*-axis is the global mean surface temperature increase in 2100 relative to 1900. The *x*-axis is the value of the equilibrium temperature sensitivity.
- Going across panels on the horizontal axis, the first column uses the grid value of the first of the five population scenarios (which is the lowest growth rate); the middle column shows the results for the modeler's baseline population; and the third column shows the results for the population associated with the highest population grid (or highest growth rate).
- Going down panels on the vertical axis, the first row uses the highest growth rate for TFP (or the fifth TFP grid point); the middle row shows TFP growth for the modeler's baselines; and the bottom row shows the results for the slowest grid point for the growth rate of TFP.
- The center panel uses the modeler's baseline population and TFP growth. It indicates how temperature in 2100 across models varies with the equilibrium climate sensitivity (ECS), with the differences being 1.5 °C between the ECS grid points. A first observation is that the models all assume that the ECS is close to 3 °C in the baseline. Next, is that the resulting baseline temperature increases for 2100 are closely bunched between 3.75 and 4.25 °C. All curves are upward sloping, indicating that a greater 2100 temperature change is associated with a higher ECS.
- As the ECS varies from the baseline values, the model differences are distinct. These can be seen in the slopes of the different model curves in the middle panel. The impact of a 1 °C change in ECS on 2100 temperature varies by a factor of 2½ across models. For example, DICE, MERGE, and GCAM have relatively responsive climate modules, while IGSM and FUND climate modules are much less responsive to ECS differences.

7.8 Fat tails and climate change policy

A **tail event** can be regarded as an extreme event which occurs outside the range of what is normally expected. A tail event is an outcome which, from the perspective of the frequency of historical events or perhaps only from intuition, should happen very rarely. The probability and trends of extreme environmental events are hard to determine because the events are rare. Nonetheless, observed probability distributions of many kinds of extreme environmental events follow thick-tailed, in contrast to thin-tailed, probability distributions. According to these distributions, the next extreme event above a threshold will be much more severe than the previously-observed extreme. This property is not intuitive, but clearly it should be recognized in planning, management and research for environmental extreme events, including climate change policies (see Carpenter et al., 2012).

The expected value of an extreme event above a threshold in thin-tailed distributions is only a small amount greater than the threshold itself. Tail thickness can be diagnosed by plotting the mean excess (average observation above a threshold) versus the threshold. The mean excess is inversely related to the threshold in thin-tailed distributions.

Thick- or fat-tailed distributions were first noted by Pareto (1906) with regard to the distribution of wealth in Italy. Thick tails also characterize the impacts of environmental hazards such as floods, earthquakes, landslides and wildfires (Malamud, 2004, Kousky and Cooke, 2010). For thick-tailed distributions, the next extreme event may be vastly greater in impact than the previously-observed record event, therefore recent experience cannot be used to predict the severity of future events, which might cause severe damages. More precisely:

Definition 1 *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's t-distribution).*

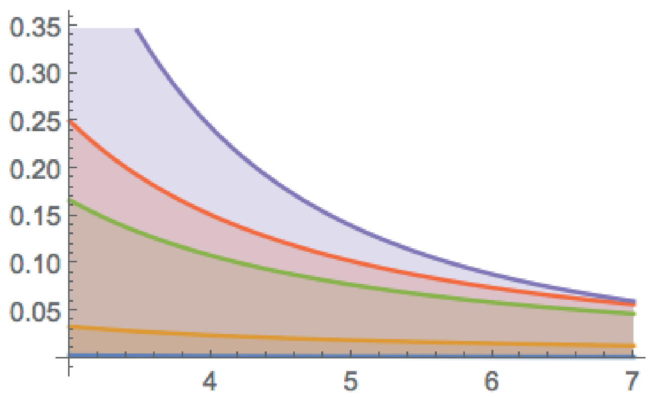

Figure 7.3. The Pareto distribution

Examples of fat-tailed and medium-tailed distributions are shown below. Figure 7.3 shows Pareto distributions.

$$P(X) = k^{\alpha} X^{-1-\alpha}\alpha\,,\ x \geq k\ \ \alpha, = \{0.01, 0.1, 0.5, 0.75, 1.5\}$$

If α is small, the tail is fat.

The fat-tailed student's *t*-distribution is shown in Figure 7.4, while the normal distribution is shown in Figure 7.5.

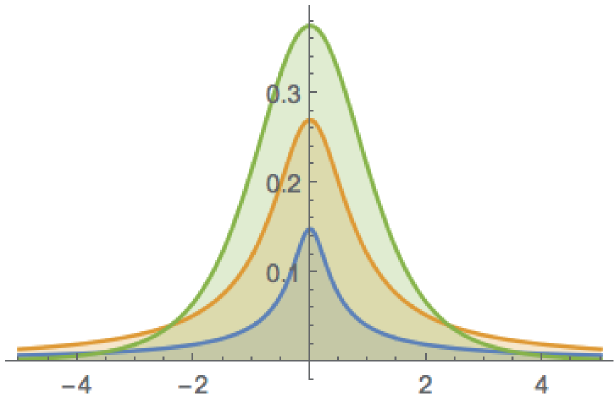

Figure 7.4. The student's *t*-distribution

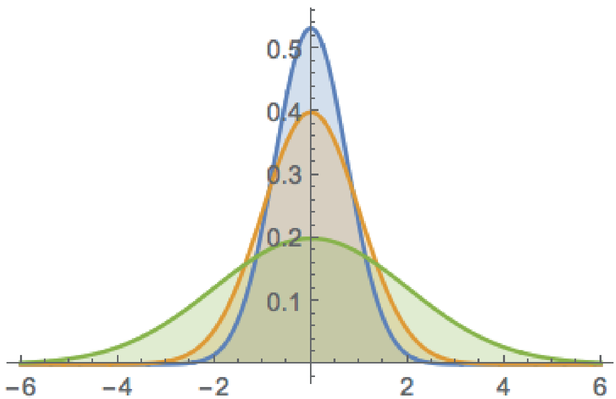

Figure 7.5. The normal distribution

7.8.1 Fat-tailed distributions and the dismal theorem in climate change

What is the relevance of tail events for climate change policy? In an important paper, Weitzman (2009, p.18) proposed what he calls a dismal theorem (see also Weitzman, 2010a). He summarizes the theorem as follows:

> In principle, what might be called 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.

The general idea is that under limited conditions concerning the structure of uncertainty and societal preferences, the expected loss from certain risks such as climate change is infinite and that standard economic analysis cannot be applied.

Let a standard utility function, defined as:

$$U(C) = \tfrac{C^{1-\eta}}{1-\eta}, \; U'(C) = C^{-\eta}.$$

Normalizing the present consumption to unity, the growth of consumption is:

$$Y = \ln C,$$

where Y is a random variable capturing all uncertainty that influences future values of $\ln C$, including damages of adverse climate change.

With time preference parameter β : $(0 < \beta < 1)$, the **stochastic discount factor** is defined as

$$M(C) = \beta \frac{U'(C)}{U'(1)} = \beta \mathrm{e}^{-\eta Y}.$$

Using the isoelastic specification for the utility function, the amount of present consumption the agent would be willing to give up in the present period in order to obtain one extra sure unit of consumption in the future period is:

$$\mathbb{E}[M] = \beta \mathbb{E}\left[\exp(-\eta Y)\right].$$

The following results can then be obtained (Weitzman, 2009):

- If Y has a probability density function $f(y)$, where y denotes a realization of the random variable Y, then

$$\mathbb{E}[M] = \int_{-\infty}^{\infty} \mathrm{e}^{-\eta y} f(y)\, dy.$$

- If $Y \sim N\left(\mu, s^2\right)$, then

$$\mathbb{E}\left[M\right] = \exp\left(-\delta - \eta\mu + \frac{1}{2}\eta^2 s^2\right),\ \delta = -\ln\beta,$$

which provides the generalization of Ramsey's rule for the SDR under uncertainty,

$$r = \delta + \eta\mu - \frac{1}{2}\eta^2 s^2.$$

- If the probability density function for $f\left(y\right)$ is the student's t, which is a fat-tailed distribution, then

$$f\left(y\right) \propto \left(1 + \frac{\left(y-\mu\right)^2}{n v_n}\right)^{-\frac{n+k}{2}},\ \text{with } n+k \text{ degrees of freedom,}$$

and

$$\mathbb{E}\left[M\right] = +\infty.$$

Formally this means that the amount of present consumption the agent would be willing to give up in the present period in order to obtain one extra sure unit of consumption in the future period is infinite.

- When $n \to \infty$, $f\left(y\right)$ becomes the normal probability density function $\exp\left(-\left(y-\mu\right)^2 / 2v_\infty^2\right)$, which is a thin- (or medium-) tailed distribution and $\mathbb{E}\left[M\right]$ is finite,

$$\mathbb{E}\left[M\right] = \exp\left(-\delta - \eta\mu + \frac{1}{2}\eta^2 s^2\right).$$

That is, 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 finite.

Taking fat tails into account has implications for climate change research and policy. For example, more emphasis should be placed on research about the extreme tails of relevant probability density functions rather than on research about central tendencies. As another example, the fatness of the bad fat tail of proposed solutions (such as, perhaps, the possibility that buried CO_2 might escape) needs to be weighed against the fatness of the tail of the climate change problem itself. With fat tails generally, we might want more explicit contingency planning for bad outcomes, perhaps including a niche role for last-resort portfolio options such as geoengineering. Qualitatively, fat tails favor more aggressive policies to lower GHGs than the standard BCA. This can be considered as an important reason to take significant action now, instead of the action implied by the gradualist policy ramp. This is a different reason for taking action now than the near zero rate of pure time preference.[24]

Pindyck (2011), in a critique of the dismal theorem, indicates that the main driver of the result is the assumption of unbounded marginal utility. Pindyck argues that unbounded marginal utility makes little sense, and once a bound is put on marginal utility, the main implication of fat tails, that is $\mathbb{E}\left[M\right]=+\infty$, goes away. Expected marginal utility will be finite even if the distribution for outcomes is fat-tailed. Furthermore, depending on the bound on marginal utility, the index of risk aversion and the damage function, a thin-tailed distribution can yield a higher expected marginal utility (and thus a greater willingness to pay for abatement) than a fat-tailed one.

Nordhaus (2011b) points out that the dismal theorem holds only under very limited conditions since it requires strong risk aversion, a very fat tail for the uncertain variables, and the inability of society to learn and act in a timely fashion. Furthermore, these properties must extend to indefinitely low consumption and indefinitely high values of the uncertain parameters. However, when the conditions of the dismal theorem are satisfied, society has an indefinitely large expected loss from high-consequence, low-probability events. In such situations, standard tools such as traditional CBA and expected utility analysis cannot easily be applied. In this respect, the dismal theorem helps identify when tail events have significance for our actions.

7.9 Deep or Knightian uncertainty in climate change

7.9.1 Preliminary concepts: expected utility

The classic paradigm of Von Neumann–Morgenstern expected utility, or its subjective extension due to Savage (1954), is still pretty much the ‘industry standard’ in most cases of decision making in the presence of uncertainty. However, there are serious concerns as to how extended its applicability is in situations where extreme risks are encountered or when there are doubts as to the validity of the probabilistic

24 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.

model used to describe or predict.

The traditional approach in dealing with risk and uncertainty in climate change economics is the von Neumann–Morgenstern expected utility framework where:

- Risk is summarized by objective numerical probabilities associated with possible outcomes.
- The decision maker maximizes expected utility assuming known numerical probability measures.

In subjective probability theory, Savage, following work by de Finetti (1931) and Ramsey (1926), established axiomatically subjective expected utility in which – even if states of the world cannot be associated with objective probabilities – the decision maker acts as if she/he is an expected utility maximizer. Thus:

- Expected utility maximization (objective or subjective) analyzes the decision-making problem in the context of risk or measurable uncertainty.
- Even when objective probabilities are not available, uncertainty is reduced to risk by expressing beliefs as subjective probabilities.

Therefore, if a decision maker faces a random variable (lottery) X and the probability measure Q can describe the distribution of X, then according to the Von Neumann–Morgenstern–Savage approach (depending on whether Q is an objective or subjective probability measure), the expected utility of X is

$$U(X) = \mathbb{E}_Q[u(X)] = \sum_{i=1}^{n} p_i u(X_i),$$

where the outcome X_i is received with probability p_i.

A probability measure Q is a real-valued function defined on a set of events in a probability space that satisfies measure properties and takes values in the interval $[0,1]$.[25]

[25] A probability space consists of three parts:

1. A sample space, Ω, which is the set of all possible outcomes of an experiment or a lottery.
2. A set of events, $\mathcal{F}$, where each event is a set containing zero or more outcomes.
3. The assignment of probabilities to the events; that is, a function Q from events to probabilities, $Q : \mathcal{F} \to [0,1]$.

7.9.2 Knightian uncertainty, deep uncertainty or ambiguity

Since the mid-twentieth 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 decision maker should have her own subjective probabilities, and that these probabilities should guide her decisions.

However, Knight (1921) and Keynes (1973) 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.

This could happen, for example, if there as doubts as to whether Q is the right model for describing the distribution of X, or if there is more than one model about X which cannot be distinguished by using existing data. This situation is usually referred to as **Knightian uncertainty** or **model uncertainty** or, more recently, as **deep uncertainty** or **ambiguity.**

The recent literature has focused on modeling and understanding the effects of the absence of a single probability model for the risk X, and is centered around the concepts of model uncertainty (i.e., absence of knowledge concerning the true probabilistic model) and uncertainty or ambiguity aversion (e.g., Ellsberg's paradox (Ellsberg, 1961)).

- Deep uncertainty in the context of climate change is mainly associated with the natural system, and characterizes an environment where ambiguity and concerns about model misspecification are present and significant. As Weitzman (2009) points out, the high structural uncertainty over the physics of environmental phenomena makes the assignment of a precise probabilistic model structure untenable, while there is high sensitivity of model outputs to alternative modeling assumptions such as the functional form of the chosen damage function and the value of the social discount rate (e.g. Stern, 2007).
- High structural uncertainty implies inability, for a decision maker or regulator, to assign a unique probability distribution to stochastic factors affecting the dynamics of climate change and the damages that climate change may cause.
- In particular, deep uncertainty or ambiguity can be regarded as a situation in which a decision maker does not formulate decisions based on a single probability model but rather on a set of probability models.

7.9.3 Maxmin expected utility

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 by arguing that, when the underlying uncertainty of the system is not well understood and the decision maker faces a set of prior probability density functions associated with the phenomenon, it is sensible – and axiomatically compelling – to optimize over the worst-case outcome (i.e., the worst-case prior) that may conceivably come to pass. Doing so guards against potentially devastating losses in any possible state of the world, and thus adds an element of robustness to the decision-making process. Thus in situations characterized by deep uncertainty, decision making should not rely on expected utility but rather, given that preferences exhibit ambiguity aversion, on maxmin expected utility.

Let the set of states of the world be Ω, (the sample space) and consider an individual observing some realization $\omega_t \in \Omega$. The basic idea underlying the multiple priors approach is that beliefs about the evolution of the process $\{\omega_t\}$ cannot be represented by a single probability measure. Instead, beliefs conditional on ω_t are too vague to be represented by such a single probability measure and are represented by a *set* of probability measures. Thus for each $\omega \in \Omega$, we consider $\mathcal{P}(\omega)$ as a set of probability measures about the next period's state.

The utility of any act α in an atemporal model is defined as (Gilboa and Schmeidler, 1989)

$$U(c) = \min_{Q \in \mathcal{P}} \int u(\alpha)\, dQ,$$

while in a continuous time framework, recursive multiple-prior utility is defined as

$$V_t = \min_{Q \in \mathcal{P}} \mathbb{E}_Q \left[\int_t^T e^{-\rho(s-t)} u(\alpha)\, ds \right].$$

These definitions of utility in the context of multiple priors correspond to an intuitive idea of the 'worst case'. Utility is associated with the utility corresponding to the least favorable prior. With utility defined in this way, decision making by using the maxmin rule follows naturally, since maximizing utility in the multiple-priors case implies the maxmin criterion.

7.9.4 Deep uncertainty and climate change

The deep uncertainty framework fits very well with climate change problems, as well as with more general environmental and resource economics problems, given the deep uncertainties associated with these issues.

For example, a specific density function for climate sensitivity from the set of 19 densities reported by Meinshausen et al. (2009) can be regarded as the benchmark model, but other possible densities should be taken into account when designing regulation. One of these densities that corresponds to the least favorable outcome regarding climate change impacts can be associated with the concept of the worst case.

The situation in which a single model – or a unique prior – is sufficient for analyzing the phenomenon and formulating decision rules can be identified as the case of pure risk or measurable uncertainty where the decision maker is able to assign probabilities to outcomes. On the other hand, the situation in which the decision maker operates in the realm of many models – or multiple priors – is the case of ambiguity or deep uncertainty. Under ambiguity, the decision maker does not have the ability to determine a precise probability structure for the physical or the economic model, or to put it differently, to measure uncertainty using a single probability model.

7.9.5 Deep uncertainty and the precautionary principle

The inability to measure uncertainty can be viewed as associating decision making and regulation under ambiguity with the concept of a **precautionary principle** (PP). Different formulations and versions of the PP can be found in the literature. Sunstein (2002-2003, 2007) discusses two versions of the PP: the weak PP where "lack of decisive evidence of harm should not be a ground for refusing to regulate"; and the strong PP, suggesting that when "potential adverse effects are not fully understood, the activities should not proceed." Sunstein regards the weak PP as sensible, but the strong PP as a paralyzing principle.

7.9.6 Robust control

Motivated by concerns about model misspecification in macroeconomics, Hansen and Sargent (2001a, 2001b, 2008) 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.

A decision maker characterized by robust preferences takes into account the possibility that the model used to design regulation, call it benchmark or approximating model $\mathbb{P}$, may not be the correct one but only an approximation of the correct one. Other possible models, say $\mathbb{Q}_1,\ldots,\mathbb{Q}_J$, which surround $\mathbb{P}$, should also be taken into account, with the relative differences among these models measured by an entropy measure. Hansen and Sargent (2003) characterize robust control as a theory "... [that] instructs decision makers to investigate the fragility of decision rules by conducting worst-case analyses," and suggest that this type of model uncertainty can be related to ambiguity or deep uncertainty so that robust control can be interpreted as a recursive version of maxmin expected utility theory.

Given the set of probability measures $\mathcal{P}$ the decision maker considers the reference probability measure $\mathbb{P}$ and another measure $\mathbb{Q}\in\mathcal{M}(\Omega)$. The discrepancy between the two measures is determined by the discounted relative entropy

$$R(\mathbb{Q}//\mathbb{P})=\int_0^{+\infty}e^{-\delta t}\mathbb{E}_Q[\frac{1}{2}h_t^2]dt,$$

where h is a measurable function associated with the distortion of the probability measure $\mathbb{P}$ to the probability measure $\mathbb{Q}$.

To allow for the notion that even when the model is misspecified the benchmark model remains a 'good' approximation, the misspecification error is constrained. Thus we only consider distorted probability measures $\mathbb{Q}$ such that

$$R(\mathbb{Q}//\mathbb{P})=\int_0^{+\infty}e^{-\delta t}\mathbb{E}_Q[\frac{1}{2}h_t^2]dt\leq\eta<\infty. \tag{7.22}$$

Using (7.22) as the entropy constraint, Hansen and Sargent (2008) define two robust control problems, a constrained robust control problem and a multiplier robust control problem. A constrained robust control problem is written as:

$$\max_{c(t)}\min_{h(t)}\mathbb{E}_0\int_{t=0}^{\infty}\mathrm{e}^{-\rho t}u(c(t),x(t))dt$$

subject to

$$d(x)=\left[F(x(t),c(t))+\sigma\left(x(t)h(t)\right)\right]dt+\sigma\left(x(t)\right)dZ(t)$$

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

where $\{Z(t),t\geq 0\}$ is a Brownian motion in the underlying probability space $(\Omega,\mathcal{F},\mathbb{P})$ and $h(t)$ is a measurable drift distortion which reflects the fact that the probability measure $\mathbb{P}$ is replaced by another measure $\mathbb{Q}$. The drift distortion incorporates omitted or misspecified dynamic effects on the dynamics of the state variable.

7.9.7 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 constrained control problem:

$$\max_E \min_h \mathbb{E}\int_0^\infty e^{-\rho t}\left[aE - \frac{b}{2}E^2 - \frac{\gamma}{2}(S - S_0)^2\right]dt \tag{7.23}$$

subject to

$$dS(t) = (mS_0 + E - mS + \sigma h)dt + \sigma dB\,,\; S(0) = S_0 \tag{7.24}$$

$$\int_0^{+\infty} e^{-\delta t}\mathbb{E}_Q[\frac{1}{2}h_t^2]dt \le \eta, \tag{7.25}$$

or the multiplier problem:

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

subject to (7.24).

Results indicate that, depending on the cost of damage-control technology and the magnitude of deep uncertainty – reflected in θ – it may be preferable to be precautious now by undertaking large damage-control investment, and not be particularly precautious with respect to future mitigation policy. When this is the case, current damage-control investment and future mitigation act as substitutes. On the other hand, when damage-control investment is costly, it can act as a complement to future mitigation and an increase in uncertainty induces precaution with respect to both policy actions.

7.9.8 Smooth ambiguity

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.

An act f is preferred to an act g if

$$\mathbb{E}_p\varphi(\mathbb{E}_\pi u \circ f) > \mathbb{E}_p\varphi(\mathbb{E}_\pi u \circ g),$$

where u is a von Neumann–Morgenstern utility function, φ is an increasing function, and p a subjective second-order probability over a set of probability measures Π that the decision maker considers to be relevant to her decision problem. The function φ is concave $\left(\varphi'' < 0\right)$ and the concavity of φ reflects **ambiguity aversion.**

Following Millner et al. (2010), suppose that Π is the set of distributions for climate sensitivity S, indexed by $m \in \mathcal{M}$, and that the choice variable is the level of abatement a of GHG emissions. For each probability model, write the expected utility obtained under that model as a function of a as

$$\mathbb{E}U_m\left(a\right) = \int u\left(a\left(S\right)\right)\pi_m\left(S\right)dS.$$

Then the policymaker's objective function can be written as

$$V\left(a\right) = \sum_m p_m \varphi\left(\mathbb{E}U_m\left(a\right)\right) =$$
$$= \mathbb{E}_{subj}\varphi\left(\mathbb{E}_{obj}U\left(a\right)\right),$$

where p_m is a second-order weight on probability model m, and the subscript notation emphasizes that the p_m are subjective weights between models, while $\mathbb{E}U_m$ denotes conditionally objective expectations taken within a given model.

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.

7.10 Regional issues

7.10.1 The RICE-2011 model

The RICE model is a regionalized version of the DICE model. It has the same basic economic and geophysical structure, but contains a regional disaggregation. The full version is described in Nordhaus (2011a). The RICE-2011 model divides the world into 12 regions. These are: the US, EU, Japan, Russia, Eurasia (Eastern Europe and several former Soviet Republics), China, India, the Middle East, Sub-Saharan Africa, Latin America, Other high income countries, and Other developing countries.

The general objective in RICE is a Bergson-Samuelson social welfare function over regions of the form $W = \mathrm{W}\left(U^1,\ldots,U^N\right)$, where U^i is the utility function in region $i = 1,\ldots,N$.

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

where $\psi_{i,t}$ are Negishi weights on each region and each time period. Each region has individual consumption, production, industrial emissions and population. In principle, the regions may have different rates of time preference, ρ. Thus net output and damages in RICE have a regional structure defined as:

$$Q^i(t) = \Omega^i(t)[1 - \Lambda^i(t)]Y^i(t)\,,\ \Omega(t) = \frac{D(t)}{1 + D(t)}$$

$$D(t) = f_1 T_{AT}(t) + f_2 SLR(t) + f_3 M_{AT}(t)$$
$$\approx \psi_1 T_{AT}(t) + \psi_2 [T_{AT}(t)]^2,$$

where $\Lambda^i\left(t\right)$ are abatement costs in region i, $\Lambda^i\left(t\right) = \theta_{1,i}\left(t\right)\left[\mu^i\left(t\right)\right]^{\theta_{2,i}}$ and $\mu^i\left(t\right)$ is the emissions reduction rate.

The damage function in the RICE-2011 model is built up from estimates of the damages of the 12 regions. The function includes damages from temperature change (T_{AT}), damages from the sea-level rise $SLR\left(t\right)$, and impacts of CO_2 fertilization which are a function of atmospheric concentrations of CO_2 (M_{AT}). The approximation equation reflects the fact that damages can be reasonably well approximated by a quadratic in temperature over the medium term.

Industrial CO_2 emissions in each region are defined as:

$$E^i_{ind}\left(t\right) = \sigma^i\left(t\right)\left[1 - \mu^i\left(t\right)\right] A^i\left(t\right) K^i\left(t\right)^{\gamma} L^i\left(t\right)^{1-\gamma},$$

where $\sigma^i\left(t\right)$ is the regional carbon intensity.

Negishi weights

The welfare weights are the reciprocal of marginal utility, or the so-called **Negishi weights**. The Negishi algorithm in the RICE model sets each of the weights so that the marginal utility of consumption is equal in each region and each period, which ensures that the requirement for maximization in the context of competitive markets is satisfied. In terms of the Second Theorem of Welfare Economics, any solution of the planner's problem for any arbitrary non-negative set of welfare weights across regions will satisfy the conditions for competitive equilibrium except for the budget constraint in each location. Budget constraints can be satisfied with appropriate transfers across locations. Thus a solution to the planner's problem resulting from a specific choice of welfare weights can be implemented as a competitive equilibrium with transfers across locations. The choice of zero transfers corresponds to the case of using the Negishi weights as welfare weights.

Regional results

The regional estimates of the SCC derived by RICE are shown in Table 4.3 in Chapter 4.

7.10.2 Spatial models of the economy and climate

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; and
- 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. These damages depend primarily on the production characteristics (e.g., agriculture vs services) or local natural characteristics (e.g., proximity to the sea and elevation). Regional IAMs such as RICE can be regarded as accounting for the economic-related forces.

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. In climate science terminology, models with a carbon cycle and no spatial dimension are zero-dimensional models which do not include spatial temperature heterogeneity effects due to heat transportation across space. In contrast, the one-dimensional or two-dimensional energy balance climate models (EBCMs) model heat transport across latitudes or across latitudes and longitudes (e.g. North, 1975a, 1975b, North et al., 1981, Kim and North, 1992, Wu and North, 2007). One-dimensional EBCMs predict a concave temperature distribution across latitudes with the maximum temperature at the Equator.

In the economics of climate, a small literature on spatial equilibrium models has recently begun to emerge (Brock et al., 2013, Brock et al., 2014a, 2014b, Desmet and Rossi-Hansberg, 2015, Hassler et al., 2016b, Brock and Xepapadeas, 2017). The main questions that this new literature is attempting to answer relate to the geographic impact of climate change on the spatial structure of climate change policies, and on the policy bias introduced by ignoring the natural mechanisms which cause non-uniform spatial distribution of surface temperature.

Statistical downscaling

One approach for introducing spatial aspects is statistical downscaling. **Statistical downscaling**, also referred to 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 (Desmet and Rossi-Hansberg, 2015, Hassler et al., 2016b, Krusell and Smith, 2017).

One-dimensional Energy Balance Climate Models with human forcing

Another approach for introducing spatial aspects involves the development of one-dimensional EBCMs. One-dimensional EBCMs describe spatial temperature heterogeneity caused by heat transportation, or flux, across space. Let x denote the sine of the latitude. For simplicity we will just refer to x as 'latitude'. Following North (1975a, 1975b), let $I(x,t)$ denote outgoing infrared radiation to space measured in $\mathrm{W/m^2}$ at latitude x at time t, and $T(x,t)$ denote surface (sea level) temperature measured in °C at latitude x at time t. The outgoing radiation and surface temperature can be related through the empirical formula

$$I(x,t) = A + BT(x,t),\ A = 201.4\mathrm{W/m^2},\ B = 1.45\mathrm{W/(m^2)(°C)}.$$

The basic energy balance equation developed in North (1975a, equation (29)), with human input added, can be written as:

$$\begin{aligned}\frac{\partial T(x,t)}{\partial t} = QS(x)\alpha(x,x_s(t)) - \left[I(x,t) - F_h(x,t)\right] + \\ D\frac{\partial}{\partial x}\left[(1-x^2)\frac{\partial T(x,t)}{\partial x}\right],\end{aligned} \tag{7.26}$$

where $x = 0$ denotes the Equator, $x = 1$ denotes the North Pole, and $x = -1$ denotes the South Pole; Q is the solar constant divided by 2; $S(x)$ is the mean annual meridional distribution of solar radiation which is normalized so that its integral from -1 to 1 is unity; $\alpha(x,x_s(t))$ is the absorption coefficient or co-albedo function which is one minus the albedo of the earth-atmosphere system, with $x_s(t)$ being the latitude of the ice line at time t; and D is a heat transport coefficient. This coefficient is an adjustable parameter which has been calibrated to match observed temperatures across latitudes. It is measured in $\mathrm{W/(m^2)(°C)}$.

Human forcing is defined by

$$F_h(t) = \frac{\eta}{\ln 2}\ln\left(\frac{S(t)}{S_0}\right),$$

where S_0 denotes the pre-industrial concentration of atmospheric CO_2 in the atmosphere, $S(t)$ is the concentration at time t, and η is a temperature-forcing parameter, or climate sensitivity (°C per W per m^2).

The stock of CO_2 evolves according to:

$$\dot{S}(t) = \int_{x=-1}^{x=1} E(x,t)\,dx - dS(t),\ S(0) = S_0,$$

where $E(x,t)$ are emissions generated at latitude x, with emissions being proportional to the amount of fossil fuels used by latitude x at time t.

In equilibrium, the incoming absorbed radiant heat at a given latitude is not matched by the net outgoing radiation and the difference is made by the meridional divergence of heat flux which is modeled by the term

$$D\frac{\partial}{\partial x}\left[(1-x^2)\frac{\partial T(x,t)}{\partial x}\right].$$

This term explicitly introduces the spatial dimension stemming from the heat transport into the climate model.

One of the differences between statistical downscaling and EBCMs is that EBCMs model heat flux across space as the mechanism of temperature's spatial heterogeneity, while statistical downscaling does not provide such a generating mechanism, but rather a representation of the underlying mechanism's outcome through the use of empirical functions.

Another realistic aspect of EBCMs is the presence of an endogenous ice line which is determined dynamically by the condition:

$$T > -T^{\circ}\text{C} \quad \text{no ice line present at latitude } x$$

$$T < -T^{\circ}\text{C} \quad \text{ice line present at latitude } x$$

where $-T$ is empirically determined (e.g., -10 °C). Below the ice line, absorption drops discontinuously because the albedo jumps discontinuously, which means that the reflective capacity of earth is reduced. This is a positive feedback to temperature increase. For example, North (1975a) specifies a discontinuous co-albedo function:

$$\alpha(x, x_s) = \begin{cases} \alpha_0 = 0.38 & |x| > x_s \\ \alpha_1 = 0.68 & |x| < x_s \end{cases}.$$

One-dimensional EBCMs produce concave temperature distributions which are in agreement with observations (e.g. North 1975a, Figures 1 and 2).

The use of one-dimensional 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 (PDEs) as constraints (Brock et al., 2013, Brock et al., 2014b). This is because temperature dynamics are modeled by a PDE (7.26) and not the usual ordinary differential equations (ODEs) presented earlier. This makes the analysis of the coupled economic–climate very complex, since the dynamic optimization problem is constrained by PDEs and not ODEs as in standard optimal control theory. Solutions of these problems usually require the use of approximation methods which transform the PDE (7.26) into a finite number of ODEs (see Brock et al., 2013, Brock et al., 2014a, 2014b). Although this provides a solution method, the number of ODEs used to approximate the PDE increase the dimensionality of the optimal control problem, which complicates the solution.

A simpler approach is to substitute the continuous space implied by (7.26) with the so-called two-box models, which split each hemisphere into two regions, one toward the Equator and one toward the Poles.

Two-box climate models

The two-box energy balance model introduced by Langen and Alexeev (2007) and Alexeev and Jackson (2013) consists of a single hemisphere with two boxes or regions divided by the 30th latitude, which yields similar surface area of the two boxes. Following Langen and Alexeev (2007), the two-box model is presented in Figure 7.6.

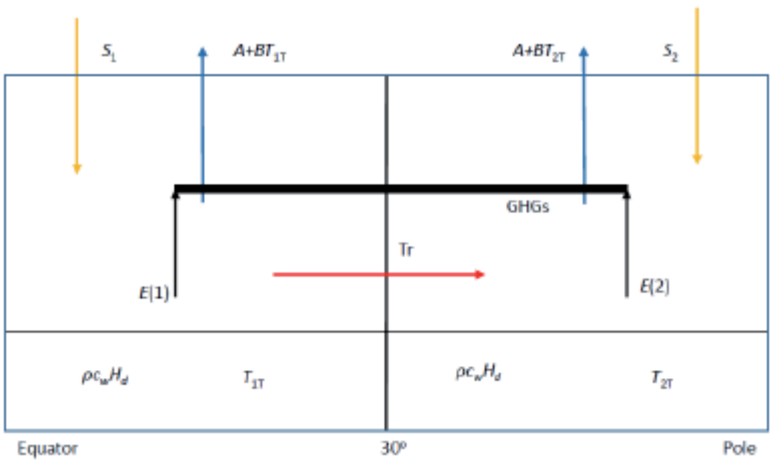

Figure 7.6. A two-box model

Source: Brock and Xepapadeas, 2017.

Assuming no anthropogenic forcing, the evolution of the ocean mixed-layer temperature in each box is:

$$\dot{T}_{1T} = \frac{1}{H}\left(S_1 - A - BT_{1T} - Tr\right) \tag{7.27}$$

$$\dot{T}_{2T} = \frac{1}{H}\left(S_2 - A - BT_{2T} + Tr\right). \tag{7.28}$$

The meridional heat transport is defined in terms of the temperature anomaly as:

$$Tr = \bar{Tr} + \gamma_1\left(T_1 - T_2\right) + \gamma_2 T_1. \tag{7.29}$$

In (7.29), the first term, $\bar{Tr}$, is the equilibrium heat transport, the second term captures the increase in transport due to increasing baroclinicity, while the third term captures the effect of an increased moisture supply and thus greater latent heat transport with increased low- to mid-latitude temperatures.

In the two-box model, global emissions at each date t are defined as the sum of emissions in box 1, $E(1,t)$, and box 2, $E(2,t)$, or $E(t) = E(1,t) + E(2,t)$. Under the linear approximation of the anthropogenic impact, the dynamical system (7.27)–(7.28) can be expressed in terms of the evolution of the temperature anomaly in each box as:

$$\dot{T}_1 = \frac{1}{H}\left[\left(-B - \gamma_1 - \gamma_2\right)T_1 + \gamma_1 T_2 + \Lambda E(t)\right],\ T_1(0) = 0$$

$$\dot{T}_2 = \frac{1}{H}\left[\left(\gamma_1 + \gamma_2\right)T_1 + \left(-B - \gamma_1\right)T_2 + \Lambda E(t)\right],\ T_2(0) = 0$$

$$E(t) = E(1,t) + E(2,t).$$

The 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. Under PA the zonally-averaged surface temperature change at high latitudes exceeds the globally-averaged temperature change, in response to climate forcings and on time scales greater than the annual cycle. Bekryaev et al. (2010), using an extensive data set of monthly surface air temperature, document a high-latitude ($>60^\circ$ N) warming rate of 1.36 °C/century for 1875-2008, with the trend being almost two times stronger than the Northern Hemisphere trend of 0.79 °C/century.

Brock and Xepapadeas (2017) use a two-box model to study the bias in the optimal carbon taxes from ignoring heat transport and PA. Results indicate that PA could potentially generate significant climate damages and its study has been shown to be important for the design of climate policies (Brock and Xepapadeas, 2017, Cai et al., 2017).

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8 International Cooperation and Climate Change

8.1 Introduction

To successfully address climate change requires international collaboration in reducing greenhouse gases emissions. In the absence of a supranational authority, such as an international institution that could enforce compliance, sovereign countries negotiate their terms and their participation in an international environmental agreement (IEA) based on their individual benefit and cost functions. Since the socially optimal outcome cannot be enforced, IEAs differ from a typical public good, as pointed out in Chichilnisky (2012). Therefore, an IEA has to be self-enforcing in order for the participating countries to voluntarily contribute to the mitigation of the environmental problem.

The complexity and high uncertainty of climate change impacts and their unequal distribution across countries make the formation of an IEA to mitigate the problem extremely difficult to achieve. The review of the history of international negotiations from the 1980s up to the present, which is presented in the third section of this chapter, reveals the complexity of developing a comprehensive international regime and highlights the necessity of looking to more flexible and adaptable solutions.

The formation of IEAs, and in particular of an agreement among countries to reduce their emissions of GHGs, has attracted the attention of a growing part of the literature. The economic literature approaches this issue using mainly game theory. Game theoretic modeling is a useful tool for the analysis of the behavior of interrelated players. Countries are considered to be rational players that act according to their own interests, but they are interrelated through the damages from climate change which depend on aggregate GHG emissions. Thus, each country’s choices affect the decisions of all the rest. An IEA on climate change must be carefully crafted so as to provide the right incentives to countries in order for them to voluntarily join the climate coalition. The following section reviews the literature on the formation of an IEA on climate change.

8.2 Review of the literature

The economic literature on the formation of a climate coalition can be categorized into three main branches, according to the assumptions made regarding countries' behavior.

The first branch considers the formation of an IEA as a voluntary provision of a public good – or a public bad, since we are dealing with emissions – and it is formalized as a cooperative game (Murdoch and Sandler, 1997). When the problem is solved as a cooperative game, it could yield the full participation of all countries as a stable outcome. The stability of the grand coalition is based mainly on the assumption that if one country leaves the coalition, the coalition dissolves.

The second branch of the literature is based on non-cooperative games and assumes that players can either make their decisions simultaneously (Carraro and Siniscalco, 1993) playing a Cournot game, or that the coalition of countries that agree to act assumes the role of a Stackelberg leader, while the rest of the countries act as followers (Barrett, 1994a, Diamantoudi and Sartzetakis, 2006). The results of both the simultaneous move and the leadership models yield very pessimistic results: only a very small coalition, consisting at maximum of four countries, is stable. The main assumption driving the pessimistic results of the non-cooperative model 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.

More recently, the introduction of farsighted behavior has been able to reconcile the above two approaches. The assumption of farsighted countries provides a more realistic framework, assuming that when a country defects from the agreement, it makes no exogenously imposed assumptions regarding the behavior of the remaining members of the agreement. Instead, it foresees what their reaction(s) will be, and which equilibrium agreement will result from such an initial deviation. Using the notion of a farsighted stable set, Diamantoudi and Sartzetakis (2015, 2017) show that larger coalitions – relative to those predicted by the myopic non-cooperative models – can be stable, including the grand coalition. The above models have been extended to a dynamic framework, which approximates climate change much more closely since it introduces stock instead of flow pollutants, but unfortunately without changing the dismal result of the static literature. It is only when repeated games are considered, allowing for effective punishment of deviators, that the size of stable coalitions increases.

In addition to the different modeling approaches above, a number of papers examine alternative ways in which membership of environmental coalitions can be enlarged. On the one hand, a number of benefits to increase the size of the coalition have been proposed, including side payments such as monetary transfers; R&D cooperation; and issue linkages such as the fight against terrorism or the suppressing of illegal drug trade, in order to balance the costs of taking environmental action. On the other hand, various punishments for the deviators – in order to sustain the size of the coalition – have been considered, including trade sanctions that reduce free-riding incentives. Obviously side payments involve costs to coalition members, but punishment may also involve costs to the punishers, incurred in the process of imposing costs on the punished. Sharing these costs of increasing and sustaining the size of the coalition also involves a very delicate negotiation process. Apart from the economic incentives that coalition members should have in order to engage in such actions, these actions may be driven by altruism or reputation effects as well (Sigmund, et al., 2001, Fowler, 2005).

8.2.1 Basic model

We will present the basic model that, abstracting from other issues such as transfers and linkages, focuses on simple games in which countries make choices based only on their level of emissions. With very few exceptions, this literature assumes that only a single coalition can be formed and assumes that countries are symmetric. We will examine the literature attempting to relax these assumptions later.

Non-cooperative games

As mentioned above, there are three main strands in the literature: non-cooperative games, cooperative games and games with farsighted stability. Under the non-cooperative approach, a country that contemplates joining or defecting from the coalition assumes that no other country will change its decision regarding participation in the coalition as a result of its own decision.

In order to determine the stable size of the coalition in equilibrium, this literature applies the notions of internal and external stability of a coalition that were originally developed by D'Aspremont et al. (1983) and extended to the formation of IEAs by Carraro and Siniscalco (1993) and Barrett (1994a). Furthermore, it is assumed that members of the coalition act cooperatively, maximizing their joint welfare, while non-members act in a non-cooperative way, maximizing own welfare. Finally, it is also assumed that, in the second stage, all countries decide their emission level simultaneously.

There exist n identical countries, $N = \{1,...,n\}$, each deriving benefits from the production and consumption of goods and services which generate emissions $e_i \geq 0$ of a global pollutant (GHG) as a byproduct. Abstracting from issues related to emission and abatement technologies, it is assumed that a simple one-to-one relationship between goods and services and emissions exists, which allows country i's benefits to be specified as a function of its emissions, $B_i(e_i)$. The benefit function is assumed to be differentially strictly concave, that is,

$$B(0) = 0, B' \geq 0 \text{ and } B'' < 0.$$

Given that global pollutants are considered, each country's damages depend on the aggregate level of pollution, $D_i(E)$, where $E = \sum_{i \in N} e_i$. The damage function is assumed differentially strictly convex, that is,

$$D(0) = 0, D' \geq 0 \text{ and } D'' > 0.$$

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:[26]

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

The process of the countries' decisions is modeled as a two-stage game and the literature examines the existence and stability of a self-enforcing coalition aimed at controlling emissions. In the first stage, each country i decides whether or not to join the coalition and form an IEA. In particular, a set of countries $S \subset N$ sign an agreement and $N \setminus S$ do not. Denote the size of the coalition by $|S| = s$, total emissions generated by the coalition by E_s, while emissions of each member of the coalition by e_s, such that $E_s = se_s$. Similarly, each non-signatory country emits e_{ns}, giving rise to a total emission level generated by all non-signatories, $E_{ns} = (n-s)e_{ns}$. The aggregate emission level is

$$E = E_s + E_{ns} = se_s + (n-s)e_{ns}.$$

26 Alternatively, the model can be specified in terms of abatement rather than emissions (Barrett, 1994). Under this specification, countries derive benefits from aggregate abatement Q, with country i's benefits given by $B_i(Q) = \frac{\hat{b}}{n}(\hat{a}Q - \frac{1}{2}Q^2)$. Each country's costs depend on its own abatement, that is, $C_i(q_i) = \frac{\hat{c}}{2}q_i^2$, where $\hat{b}$, $\hat{a}$ and $\hat{c}$ are positive parameters. The two specifications are equivalent since, if we define each country's uncontrolled level of emissions as, $\bar{e} = a$, the country specific and aggregate abatements are defined as $q_i = \bar{e} - e_i$, and $Q = \bar{E} - E = na - E$, respectively. Diamantoudi and Sartzetakis (2006) demonstrate the equivalence.

In the second stage, each country chooses its emission level. The game is solved by backward induction. In the second stage, non-signatories behave non-cooperatively, choosing their emissions by maximizing w_i. Signatories choose their emissions by maximizing the coalition's aggregate welfare, sw_s. Substituting the equilibrium values of the emission levels e_s, e_{ns} and E into the corresponding welfare functions, we derive the indirect welfare function of the signatories, ω_s, and of the non-signatories, ω_{ns}.

In the first stage, countries decide whether or not to join the coalition. In order to determine the size of the stable IEA, denoted by s^*, we use the internal and external stability conditions. The internal stability condition ensures that if a country were to defect unilaterally, its gains from free-riding would be outweighed by the adjustment (due to its defection) of the emission levels of the remaining members of the IEA. The external stability condition ensures that no other non-signatory country finds it beneficial to unilaterally join the IEA. Formally, the internal and external stability conditions are:

$$\omega_s(s^*) \geq \omega_{ns}(s^* - 1) \text{ and } \omega_s(s^* + 1) \leq \omega_{ns}(s^*),$$

respectively.

With respect to the sequence of the moves in the second stage, the literature offers two approaches. Some papers assume that the coalition and non-members move simultaneously (Cournot games) (Carraro and Siniscalco, 1991, Rubio and Casino, 2001, Finus, 2003). Using the quadratic benefits function and the quadratic or linear damage functions, the literature finds that the maximum size of the stable coalition is three.

Alternatively, some other papers assume that the coalition acts as a Stackelberg leader vis-a-vis the non-members (Barrett, 1994a, Diamantoudi and Sartzetakis, 2006, Rubio and Ulph, 2006). Diamantoudi and Sartzetakis (2006), using quadratic benefit and damage functions, find that when the set of parameters is restricted to ensure that equilibrium emission levels are strictly positive, the maximum stable size of the coalition is four. Barrett (1994a) shows that larger-size coalitions could be formed, but this happens only if we allow for very high levels of abatement leading to negative emissions (in which case gains to cooperation are small). The work of Rubio and Ulph (2006) supports larger coalitions as well, by explicitly considering corner solutions, that is, when equilibrium emissions equal zero.

The above literature shows that not only is the size of the stable coalition small, but also that countries' net benefits are very low. This is due to the definition of external and internal stability conditions, the combination of which defines the size of the stable coalition below the intersection(s) of the signatories' indirect welfare function $\omega_s(s)$, with the non-signatories' indirect welfare function shifted by one, $\omega_{ns}(s-1)$, as shown in Figure 8.1.

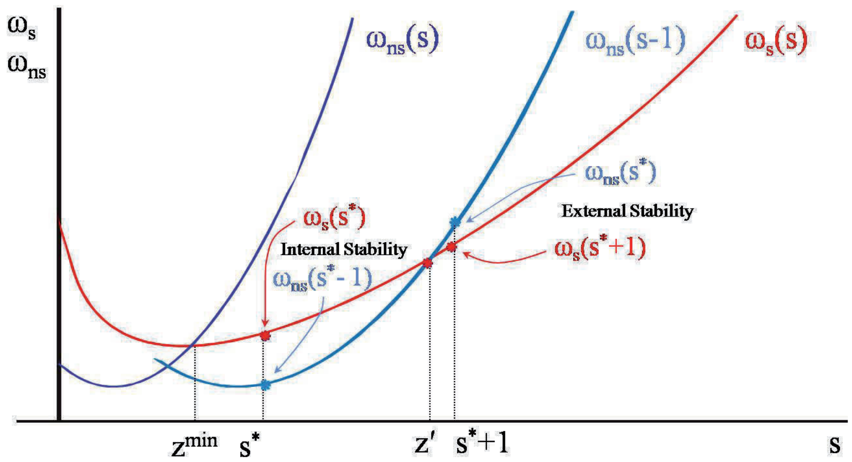

Figure 8.1. Stable size of the coalition under myopic non-cooperative behavior

Figure 8.1 illustrates the signatories' and non-signatories' indirect welfare as a function of the coalition's size, s. Diamantoudi and Sartzetakis (2015) show that under general strictly concave benefits and strictly convex damage functions, and using the leadership game, $\omega_{ns}(s)$ cuts $\omega_s(s)$ from below at $z^{\min}$ which is the minimum of $\omega_s(s)$. As can be seen, the size of the stable coalition(s) depends on the curvature of the indirect welfare functions[27] and the number of coalitions depends on whether the two curves intersect only once or multiple times.

Under general strictly concave benefits and strictly convex damage functions only, $\omega_s(s)$ can be proved to be monotonically increasing after $z^{\min}$, and thus multiple intersections cannot be excluded (Diamantoudi and Sartzetakis, 2017). In the case of quadratic cost and benefit functions, both indirect welfare functions are monotonic and only a single stable coalition exists. In such cases, the size of the stable coalition is very close to the $z^{\min}$, and therefore is slightly larger than that for which the welfare of the signatories is at its minimum.

27 Sartzetakis and Strantza (2013) show that if the model is extended to include the abatement option, the curvature of the indirect welfare function changes, allowing for larger stable coalitions.

The static non-cooperative Cournot and Stackelberg games demonstrate that free-riding incentives are very strong, leading to dismal coalitions yielding very low net benefits. This result does not substantially change if we consider stock instead of flow pollutants, except for the case in which a minimum participation clause is assumed (in such a case, if one country deviates, the coalition is dissolved) as in Rubio and Casino (2005), which however makes the framework similar to cooperative games. Calvo and Rubio (2012) offer a detailed survey of dynamic IEA models. Modeling coalition formation as an infinitely repeated game, thus allowing the punishment of defectors, could sustain full cooperation (Barrett, 1999), especially if multiple coalitions are considered (Asheim et al., 2006).

Cooperative games

Departing from the assumptions of the non-cooperative games, another part of the literature on IEAs applies the core concept of stability to examine coalition formation (Chander and Tulkens, 1995, 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 will collapse and each country will fend for itself. It is clear that if an agreement is designed in such a way that deviators are indirectly yet effectively punished through the collapse of the agreement, then cooperation and social optimality may be attainable after all.

Chander (2007) also attempts to reconcile the two approaches by formalizing coalition formation as an infinitely repeated game. He shows that the grand coalition is an equilibrium outcome, because each player can credibly commit to not form a coalition unless it includes all players. That is, he is able to achieve the grand coalition, as in Chander and Tulkens (1995, 1997), without the need for the fully collapsing agreement assumption employed by the core concept. However, since the grand coalition is not the only equilibrium, the author uses Schelling's (1960) focal-point argument to select the grand coalition as the only equilibrium outcome.

This literature sheds light on the theory of IEAs from a normative angle: if an agreement is designed in such a way that deviators are indirectly yet effectively punished through the collapse of the agreement, cooperation and social optimality may be attainable after all. It also points out the importance of transfer payments, since the conditions for a non-empty core involve the use of side payments.

Farsighted games

The above two approaches yield very different results with respect to the stable size of the coalition, mainly because of the polar assumptions made regarding what the defecting country believes that the remaining members will do upon its withdrawal from the coalition. The non-cooperative approach assumes that the rest of the coalition will remain intact, while the cooperative approach assumes that defection by one country will lead to the breakup of the coalition.

The concept of farsighted stability has been used to bridge the gap between these two polar cases. It uses the concept of internal and external stability but, at the same time, it 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.

More precisely, when a country defects from an agreement, it does not make any assumption regarding the behavior of the remaining members of the coalition. Instead, it foresees what their reaction will be and which equilibrium agreement will result from such a deviation. 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 assumptions.

In the literature on IEAs, farsightedness has been discussed and encouraged by Ecchia and Mariotti (1998), Carraro and Moriconi (1998) and further developed by Eyckmans (2001). Diamantoudi and Sartzetakis (2002) formally define the concept of farsighted stability and provide the complete characterization of the farsighted stable set, allowing for the agreement to both shrink and grow in size. That is, they permit renegotiation among countries, in the sense that even if an IEA collapses, countries can always renegotiate a larger agreement.

Diamantoudi and Sartzetakis (2015) examine the case in which any group of countries may choose to coordinate their actions in either joining or withdrawing from an agreement, while in Diamantoudi and Sartzetakis (2017) they assume that countries make their choices independently. In both cases they find, using general functional forms, that not restricting countries to myopic behavior increases the set of possible stable coalitions. Diamantoudi and Sartzetakis (2017) also examine the special case of quadratic functional forms in order to compare it to the results under the myopic case. Using simulations, they show that larger coalitions are farsighted stable, relative to the myopic ones, and 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 farsighted stable coalitions, it is a possible equilibrium outcome.

These results are based on the credible threat (in the sense that it is individually optimal) of the partial collapse of the agreement once a country withdraws from the agreement. The threat of the partial collapse of the agreement reduces free-riding benefits, leading to larger stable coalitions.

The above results have been verified in a dynamic setting (Zeeuw, 2008, Biancardi, 2010), and by using a multi-regional CGE model (Lise and Tol, 2004). Benchekroun and Ray Chaudhuri (2015) also use farsighted stability and find that the impact of cleaner technologies on the stable coalition size is ambiguous.

Generalizing to asymmetric countries

One of the most restrictive and unrealistic assumptions of the above literature is the homogeneity of countries' costs and benefits. In reality, both damages suffered from a global pollutant and benefits derived from emitting the pollutant (related to production and consumption) differ among countries. Despite its apparent importance, only a few papers have addressed the issue of heterogeneity within a theoretical framework.

Assuming two types of countries, Barrett (1997) finds no substantial difference in the size of the stable coalition relative to the homogeneous case. On the contrary, McGinty (2007), allowing for transfer payments through a permit system, finds that heterogeneity can increase the coalition size. Chou and Sylla (2008) consider two types of countries, denoted as developed and developing, and provide a theoretical framework to explain why it is more likely that some developed countries will form a small stable coalition first and then engage in monetary transfers to form the grand coalition. Osmani and Tol (2010) also assume two types of countries, but allow the formation of two separate coalitions. They demonstrate that in the case of high environmental damages, forming two coalitions yields higher welfare and better environmental quality relative to a unique coalition.

Biancardi and Villani (2010) introduce asymmetry in environmental awareness and find that the coalition's stability depends on the level of the asymmetry and that the grand coalition can be obtained only by transfers. Fuentes-Albero and Rubio (2010) assume that countries differ either in abatement costs or environmental damages (which are assumed to be linear) and find that heterogeneity has no important effect without transfers but, if transfers are allowed, the level of cooperation increases with the degree of heterogeneity. Finally, Pavlova and Zeeuw (2013), assuming differences in both emission-related benefits and environmental damages (which are assumed to be linear), find that large stable coalitions are possible without transfers if the asymmetries are sufficiently large. However, they also find that gains from cooperation are very low and that transfers could improve gains from cooperation.

As the above review indicates, results of the theoretical literature are mixed. Most of the literature based on simulations finds that under some circumstances, heterogeneity may improve coalitions' effectiveness. 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.

Diamantoudi et al. (2017) – extending the standard myopic non-cooperative quadratic cost and benefit functions model – derive analytical results and prove that introducing heterogeneity in environmental damages does not increase the size of the coalition. On the contrary, if heterogeneity is strong enough, a smaller stable coalition results relative to the homogeneous case. In particular, they assume two types of countries and show that the internal stability condition holds only for coalitions with maximum two members from each type of countries. Furthermore, if the asymmetry is strong, the external stability condition holds only for coalitions consisting of one type of countries. Only for very small asymmetry is a mixed coalition, consisting of one country from each type, stable. They also prove that coalitions that are stable under symmetry may become unstable when asymmetry is introduced. Therefore, the assumption of homogeneity is not the determining factor driving the pessimistic result of the standard myopic model that the resulting coalition will be very small. Increasing the difference in costs and benefits among countries makes the agreement more difficult to achieve but – because an agreement under large differences could yield substantial aggregate benefits – considering transfer payments might stabilize a large coalition. This is why the solution of the model with asymmetric countries is considered important.

8.2.2 Models with transfers and issue linkages

An obvious extension of the basic model is to either allow direct transfer payments by coalition members, or to link participation in the IEA to other issues such as trade agreements, in order to attract new members into the coalition. As mentioned above, in order to examine the role of transfer payments and issue linkages, some type of asymmetry among countries should be introduced.

At the theoretical level, Petrakis and Xepapadeas (1996) consider country heterogeneity in damages with quadratic benefits from emissions and linear damages.

Countries differ in terms of their environmental consciousness, with the more conscious willing to provide a side payment to the less conscious countries in order for the latter to reduce their emissions. Assuming that the more conscious countries can commit to transfers and making transfers conditional on total emissions, they show that the grand coalition can be a stable outcome.

Botteon and Carraro (1997, 2001) show that even without commitment, transfers can sustain larger coalitions. Biancardi and Villani (2010), mentioned above, also show that transfers can sustain the grand coalition. McGinty (2007) introduces transfers through emission permits and shows that larger coalitions are possible.

A number of papers use integrated assessment models to assess the effects of side payments. Tol (2001) employs the Climate Framework for Uncertainty, Negotiation and Distribution (FUND) model and finds that side payments do not achieve large coalitions that include the high polluting or the most damaged countries. Finus et al. (2006) use the STACO model and show that transfer payments could stabilize larger coalitions. On the contrary, Bosetti et al. (2013) use the WITCH model to show that only the grand coalition can achieve sufficient GHGs mitigation but that it is internally unstable. Lessmann et al. (2015) compare different transfer schemes using five different IAMs (RICE, CWS, STACO, MICA and WITCH) and find that the only effective transfers are those among coalition members that ensure internal stability. As mentioned above, the cooperative game literature also uses transfers to sustain the grand coalition (Chander and Tulkens, 1995, 1997).

An alternative to side payments in promoting cooperation is to connect the climate agreement to another issue, usually trade. The main idea of this literature is to link the environmental game – in which signatories cannot exclude non-signatories from enjoying the benefits that the coalition generates – to a club good game where exclusion from enjoying the club benefits is possible.

Folmer et al. (1993) and Folmer and van Mouche (1994) consider both multiple isolated one-shot games and repeated games and show that connecting the environmental and the trade agreement games improves the possibility of cooperation. Carraro and Marchiori (2004) consider two isolated games – an environmental agreement game and a trade agreement game – and introduce an initial stage at which countries decide whether to link negotiations of the two games. They find that countries decide to link the two games only if benefits from large environmental coalitions are substantial.

Three main strands of this literature have evolved, focusing on linking the environmental game to different club games. The above-mentioned papers and

Barrett (1994b) propose linking environment discussions with trade negotiations. Carraro and Siniscalco (1995) and Hoel and Zeeuw (2010), among others, propose linking IEAs with R&D cooperation. Hoel and Schneider (1997) and others attempt to model issue linkage by introducing reputation effects. Further information can be found in literature review papers such as Ioannidis et al. (2000) and the more recent one by Marrouch and Ray Chaudhuri (2016) which also includes an extensive review on issue linkages.

8.3 History of climate negotiations

At the international level, the First World Climate Conference organized in Geneva in 1979 by the World Meteorological Organization can be considered as the first attempt to examine the issue of climate change. The conference's main effort was to evaluate the emerging body of knowledge that related higher atmospheric GHG concentrations to increases in global temperature.

Scientific research improved considerably during the 1980s and the capacity of climate models improved, decreasing the uncertainties surrounding the result that global warming is anthropogenic. Public awareness about climate change put increasing pressure on politicians globally. Since there was considerable disagreement among scientists, the World Meteorological Organization and the UN Environment Programme established the Intergovernmental Panel on Climate Change – IPCC – in 1988 to continuously review and assess emerging scientific knowledge on climate change, in order to provide policymakers with the scientific basis and options for adaptation and mitigation. In the following year, the UN Environment Programme and the World Meteorological Organization initiated negotiations for the development of a global agreement on climate change. During these negotiations,[28] the principle of 'common but differentiated responsibilities' emerged, since negotiators had to tackle the issue of how the responsibility for controlling global climate should be allocated among countries with very different current characteristics and historical GHG contributions.

The negotiations resulted in a proposal for the creation of a framework convention, which was finalized and adopted at the UN Conference on Environment and Development in Rio de Janeiro, Brazil, better known as the 'Rio Earth Summit', in 1992. The UN Framework Convention on Climate Change (UNFCCC) was one of

28 The negotiations took place during five sessions of the Intergovernmental Negotiating Committee for a Framework Convention on Climate Change.

three highly linked Conventions adopted at the Rio Earth Summit, the other two being the UN Convention on Biological Diversity and the Convention to Combat Desertification.

The UNFCCC was ratified and entered into force in 1994 with the aim of preventing 'dangerous' anthropogenic (human-induced) interference with the climate system by stabilizing GHG concentrations. The 197 countries that have up to now ratified the Convention are called **Parties to the Convention** and they participate in the sessions of the Conference of the Parties (COP) to negotiate and develop future action to battle climate change. The IPCC provides significant input in the negotiation process, mainly through the publication of IPCC assessments. The relationship between the UNFCCC and the IPCC is a very positive example of the benefits that can be attained through the interaction between the scientific community and policymakers.

Intergovernmental Panel on Climate Change

The IPCC currently has 195 members and participation is open to all member countries of the World Meteorological Organization and the United Nations. Representatives of the member states form the Panel, which meets yearly in plenary sessions and elects the members of the IPCC Bureau, its Chair and the Working Group and Task Force Co-Chairs. Currently the IPCC has three Working Groups: Working Group (WG) I assesses the physical scientific aspects of the climate system and climate change; WG II assesses the vulnerability of socioeconomic and natural systems to climate change and provides adaptation options; and WG III assesses mitigation options by reducing GHG emissions and enhancing GHG removal activities.

The IPCC also has a Task Force on National Greenhouse Gas Inventories that oversees the programme on national GHG inventories. IPCC reports are written by thousands of volunteer scientists and experts from all over the world who are involved in both writing and reviewing the reports. They are selected by the respective Working Group Bureau from national nominations or because of their recognized special expertise. The number of scientists, their geographical distribution and the topics covered by the reports is continuously growing. Of great importance is the review process, conducted in two stages, in which both governments and expert reviewers provide their comments. The final report reflects all different views expressed in the process.

The first IPCC Assessment Report, which was released in 1990, underlined the truly global character of the climate change problem, pointing to the fact that the solution to climate change requires global cooperation. This Assessment Report played an instrumental role in the negotiations leading to the development of the UNFCCC. The IPCC was called upon to provide updated information in the process of climate negotiations and prepared Supplementary Reports in 1992 and a Special Report in 1994.

The second IPCC Assessment Report, published in 1995, provided substantive input into the process of further developing the UNFCCC and, in particular, into the negotiations process that constructed the Kyoto Protocol which was adopted in 1997 (IPCC, 1995).

The Third Assessment Report was initiated in 1997 and came out in 2001. It was used as a major input at COP 8, the eighth Conference of the Parties in 2002. The Third Assessment Report confirmed that significant cuts in global GHG emissions would be necessary in order to meet the ultimate objective of the Convention (UNFCCC, 2002).

The Fourth Assessment Report (AR4) in 2007 provided new knowledge about climate drivers; identified impacts of climate changes, especially in very vulnerable areas; and evaluated emissions trends and mitigation options. AR4 provided the scientific basis that supported the Bali Action Plan adopted at the thirteenth Conference of the Parties (COP 13) in 2007 (UNFCCC, 2008).

The Fifth Assessment Report (AR5) was released in 2013 and 2014 in four different parts: three Working Group reports and a Synthesis Report integrating material from the three WG reports, and supported the process leading to the Paris Agreement. AR5 is the most comprehensive assessment of climate change yet undertaken, providing a clear and up-to-date view of the current state of scientific knowledge relevant to climate change. The IPCC has initiated the Sixth Assessment Report, which is expected to be completed in 2022, in order to support the first review of the progress that countries have made in achieving their goal of keeping global warming to well below 2 °C, a process that was agreed upon in Paris.

Apart from the five Assessment Reports, the IPCC also produces Special Reports, Methodology Reports, Technical Papers and Supporting Material. Overall, the IPCC has regularly delivered the most comprehensive scientific reports about climate change that provided a solid support for the UNFCCC negotiation process and the basis on which policies at the national and international level have been developed. For its total contribution, the IPCC was awarded the Nobel Peace Prize in 2007.

UN Framework Convention on Climate Change

In 1994, as mentioned above, countries – realizing the urgency of the climate change problem – formed the UNFCCC to provide a framework for international cooperation aimed at controlling the increase in global temperature and providing the means to adapt to inevitable impacts. In 1995 the first Conference of the Parties (COP 1) took place in Berlin, launching negotiations to control climate change (the Berlin Mandate). Two years later the Kyoto Protocol was formally adopted at COP 3 and went into effect in 2005.

Kyoto Protocol. The Kyoto Protocol legally bound developed countries that ratified the Protocol to specific, quantitative emission reduction targets. The Protocol's first commitment period started in 2008 and ended in 2012, while the second began on 1 January 2013 and ends in 2020. The main target of the first commitment period was the reduction of developed countries' GHG emissions by at least 5 percent below 1990 levels. The most controversial issue was the adoption of the principle of 'common but differentiated responsibilities' which limited the application of quantitative targets to developed countries, based on the fact that they were the source of most past and current GHG emissions. These countries, called Annex I countries, belong to the OECD and also include twelve countries from Central and Eastern Europe with 'economies in transition'.

A number of industrialized countries criticized the lack of commitment by developing countries, especially China, India, Mexico and Brazil whose GHG emissions were growing rapidly. After long and painful negotiations, the Kyoto Protocol was formed, with commitments placed only on Annex I countries. The Kyoto Protocol was never ratified by the US Congress and in 2001, George W. Bush, the newly-elected US President at that time, withdrew US support from the process.

Despite this setback, the negotiation process kept going, led primarily by the EU. In 2002 at the COP 7, the resulting agreement – the Marrakesh Accord – provided flexible compliance rules for International Emissions Trading (on which the EU ETS was based); the Clean Development Mechanism or CDM that allowed for collaborative projects with carbon credit trading between industrialized and developing countries; and joint implementation (JI), allowing for project collaboration with carbon credit trading among industrialized countries.

Finally, after making substantial concessions,[29] a number of key players that

29 These concessions included counting sequestration of carbon in soils and trees and agreeing on very flexible compliance procedures.

included Russia, Canada, Japan and Australia, ratified the Protocol in 2004, thus allowing it to enter into force.[30] Annex I countries were expected, by the year 2000, to reduce emissions to 1990 levels. Industrialized countries agreed to provide developing countries with financial assistance and share technology. Moreover, Annex I countries agreed to report regularly on their climate change policies and measures, and submit an annual inventory of their GHG emissions. Developing countries (Non-Annex I countries) that ratified the Protocol did not have any commitments, apart from providing general reports on their actions.

The Kyoto Protocol was criticized on many grounds and was considered very weak by many. The absence of major GHG contributors such as the US, the increasing contributions of China – which in 2007 became the world's biggest emitter – and the increased quotas of the participating countries through collaboration projects (CDM), were the main points that raised questions regarding the Kyoto Protocol's effectiveness.

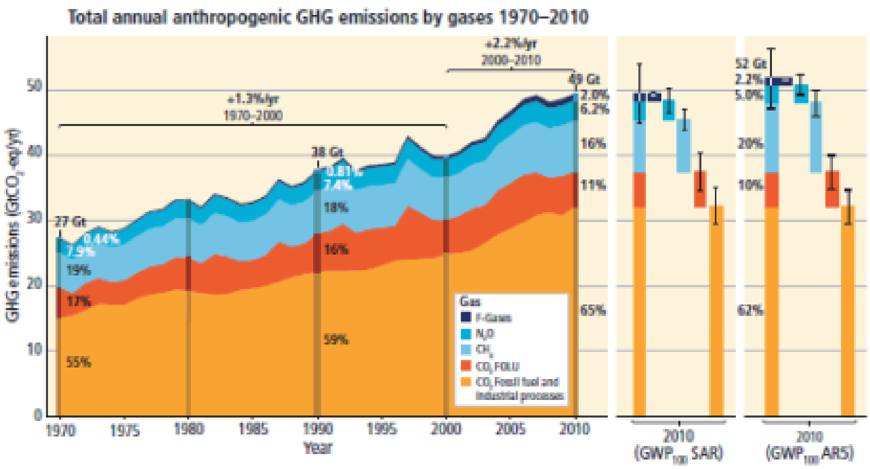

Figure 8.2. Total annual anthropogenic GHG emissions ($GtCO_2eq/yr$) for the period 1970-2010, by gases

Notes: F-gases – fluorinated gases covered under the Kyoto Protocol; N_2O – nitrous oxide; CH_4 – methane; CO_2 FOLU – CO_2 from forestry and other land use.

Source: IPCC, 2014, *Climate Change 2014. Synthesis Report. Summary for Policymakers*, Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Core Writing Team, Pachauri R.K. and L.A. Meyer (eds), IPCC, Geneva, Switzerland, Figure SPM 2.

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30 The rules demanded that at least 55 Parties to the UNFCCC ratify the Kyoto Protocol and that those include industrialized countries accounting for at least 55 percent of CO_2 emissions from industrialized countries in 1990.

Despite all these issues, many European countries managed to meet their targets, and aggregate emissions from participating countries with Kyoto targets have fallen significantly. Overall, however, global GHG emissions continued to increase, since emissions in the rest of the world have increased sharply. The IPCC (2014) shows that total anthropogenic GHG emissions continued to increase steadily from 1970 to 2010, with the largest absolute increase occurring between 2000 and 2010. As shown in Figure 8.2 (IPCC, 2014), in 2010 total annual anthropogenic GHG emissions reached 49 ± 4.5 $GtCO_2eq/yr$.

Post Kyoto negotiations. Negotiations continued even after the entry into force of the Kyoto Protocol, with the goal of developing the post-2012 phase, making an effort to keep all members of the UNFCCC participating, regardless of whether or not they had ratified the Protocol. For this reason, apart from the meetings of the Parties to the Kyoto Protocol, the Ad-hoc Working Group on Long-term Cooperative Action was established by decision of the COP 13 (the Bali Action Plan) in 2007, with participation of all UNFCCC Parties. Its main goal was to enable the implementation of the Convention by developing an agreement beyond 2012. The Ad-hoc Working Group on Long-term Cooperative Action had contributions to both the COP 16 and 17 and delivered its final outcome at the COP 18.

Despite the high expectations that were raised as the COP 15 in Copenhagen was approaching, the Copenhagen Climate Conference failed to reach a consensus on the Copenhagen Accord. Instead, the closing Copenhagen plenary agreed to “take note” of the Accord, which did not however make much difference, since it was not a legally-binding agreement but rather a political framework for continuing negotiations. The Copenhagen Accord acknowledged the need for deep cuts in global GHG emissions, postponing details, such as the emissions reduction targets for industrialized countries and emissions mitigation actions of developing countries, to be dealt with later. It was, however, the first time that mitigation targets for developing countries had been discussed, and also initiated the move from individual country targets (such as those set in the Kyoto Protocol) to national emissions limitation pledges. National pledges were supposed to add up to a joint international effort.

Discussions about national pledges continued at the COP 16 in Cancun in 2010. The agreement at the COP 17 in Durban extended the Kyoto Protocol, providing a transition period for the EU and other countries to maintain a common legal framework as they headed toward a new future agreement. The COP 18 in Doha (2012) reached an agreement to extend the life of the Kyoto Protocol until 2020, by putting substance into the 2011 Durban Platform. For this second period, the remaining Parties to the Protocol[31] committed to reducing GHG emissions by at least 18 percent below 1990 levels. Despite its limited effectiveness, the second phase of the Kyoto Protocol was instrumental in keeping the process alive.

Publication in 2013 and 2014 of the four different parts of the IPCC's Fifth Assessment Report, which was discussed above, was instrumental in gathering momentum for the negotiations leading to the COP 19 in Warsaw. AR5 made clear that stronger measures were urgently needed since existing and proposed policies would not be sufficient to keep the increase in average global temperature below 2 °C by 2100. (The path of global average temperature change projected to the year 2100 is shown in Figure 4.2 in Chapter 4.) The IPCC (2014, p. 11) indicated that:

> Relative to 1850–1900, global surface temperature change for the end of the 21st century (2081–2100) is projected to likely exceed 1.5 °C for RCP4.5, RCP6.0 and RCP8.5 (high confidence). Warming is likely to exceed 2 °C for RCP6.0 and RCP8.5 (high confidence), more likely than not to exceed 2 °C for RCP4.5 (medium confidence), but unlikely to exceed 2 °C for RCP2.6 (medium confidence).[32]

Despite these very serious concerns raised in AR5, expectations that the COP 19 would result in concrete results were not realized. Although progress was made regarding several more technical issues, such as monitoring, reporting and verification, the COP 19 did not make the expected progress toward the ultimate shape of a Paris accord, that is, a comprehensive agreement with legally-binding targets. However, countries set the first quarter of 2014 as a loose timeline for proposing their **intended nationally determined contributions**[33] to the 2015 agreement. Negotiations to reach a global, legally-binding agreement continued at the COP 20 in Lima and efforts were made to prepare the ground for the Paris meeting by drafting a partial agreement for the COP 21. Accepting proposals from developing countries, the COP 20 recognized adaptation as equally important to

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31 By that time, Canada (which withdrew in 2012), Japan, Russia, Belarus, Ukraine, New Zealand and the United States were not participating, and China, India and Brazil did not have commitments, thus limiting the scope of the second period to only 15 percent of the global CO_2 emissions.

32 Representative concentration pathways or RCPs are GHG concentration trajectories adopted by AR5. The four RCPs – RCP2.6, RCP4.5, RCP6, and RCP8.5 – describe four possible climate futures, depending on the amount of GHGs emitted in the years to come, and are named after a possible range of radiative forcing values in the year 2100 relative to pre-industrial values (+2.6, +4.5, +6.0, and +8.5 W/m2, respectively). For more information on RCPs, see Section 4.1 in Chapter 4.

33 Note that the term `contribution' replaced the term `commitment' in describing the proposals that would be made by developed and developing countries.

mitigation and connected the National Adaptation Plans to financial support from the Green Climate Fund.

Paris Agreement. Even though the previous COPs were not considered successful, they paved the way for the first legally-binding and truly global climate change agreement which was the outcome of the COP 21 in Paris in 2015. 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 and at the same time maintaining 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 percent of the total global GHG emissions was achieved. Today, 147 out of the 197 Parties to the Convention have ratified the Agreement, including all major players. The first session of the COP serving as the Meeting of the Parties to the Paris Agreement took place in Marrakesh, Morocco in November 2016.

The main achievement of the Paris Agreement is the balance between legally-binding elements, especially in the process of measuring and evaluating progress by all parties, and flexibility in establishing country specific targets and implementation policies through the **nationally determined contributions** (NDCs). 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, thus eliminating the strict distinction between Annex I and non-Annex I countries that existed under the Kyoto Protocol. The principle of common but differentiated responsibility took on another meaning, allowing countries to match their contributions to their capacities and circumstances, thus enabling broad participation.

The Paris Agreement also contains significant elements regarding adaptation. It was agreed to strengthen societies' ability to deal with the impacts of climate change and also to provide continued and enhanced international support for adaptation to developing countries. The Agreement also recognizes the importance of averting, minimizing and addressing loss and damage associated with the adverse effects of climate change and acknowledges the need to cooperate and enhance the understanding, action and support in different areas such as early warning systems, emergency preparedness and risk insurance.

Furthermore, the Paris Agreement includes elements of financial support, especially toward the Least Developed Countries. Article 6 of the Paris Agreement re-introduces carbon markets by providing the opportunity to expand the reach of carbon pricing to enable implementation of NDCs. It describes the use of **internationally transferred mitigation outcomes** and establishes an Emissions Mitigation Mechanism to contribute to the mitigation of GHG emissions. These two mechanisms, the Emissions Mitigation Mechanism and the internationally transferred mitigation outcomes, could be designed to promote a global carbon pricing. The Emissions Mitigation Mechanism could offer a universal carbon allowance or credit for those countries that choose to use it, facilitating trade between NDCs (that is, internationally transferred mitigation outcomes), providing registry facilities and therefore offering the prospect of carbon pricing at a global level. These mechanisms present an improvement over the CDM, since they provide for a net mitigation impact. Given the conclusions of Chapter 5 regarding cap-and-trade policies, connecting multiple allowance markets could yield significant cost reductions.

8.3.1 Summary and critical evaluation

The theoretical literature that was briefly summarized earlier in this chapter highlights the strong free-riding incentives that exist in climate change negotiations and that become more prominent when high asymmetry is introduced between countries. The fact that, under farsighted behavior, multiple stable coalitions exist, indicates the sensitivity of the coalition size to the initially proposed agreement. Furthermore, introducing transfer payments and issue linkages clearly improves the size of the coalition. Finally, allowing multiple agreements to be formed also leads to more countries taking actions.

The evolution of climate change negotiations shows that multiple regimes have formed that attempt to mitigate GHG emissions. Although most of the effort clusters around the UNFCCC, there are many other activities as well – either at the international level, such as the discussions under the G8 and G20 forums and the Prototype Carbon Fund of the World Bank, or at the national or local levels, such as the markets for carbon allowances that were discussed in Chapter 5, including the Korean ETS, the CaT and the RGGI.

Thus it appears that it might be more effective to form a variety of arrangements to curb GHGs, allowing for flexibility and at the same time trying to interconnect them and put them under the same framework, rather than insisting on a single integrated agreement with specific targets. The Paris Agreement is clearly a move in this direction, creating a truly multilateral framework that combines legal commitments and flexibility. However, many challenges are anticipated during its implementation.

One interesting question is whether the position of the US president in 2017 to remove the United States from the Paris Agreement will strengthen or weaken the agreement. Given the flexibility that the Paris Agreement provides, it remains the responsibility of the key players to develop concrete action that will be supported by the business sector. Thus, even if a large player such as the United States opts out (at least for some time), other countries – or even local activities within the United States – might step up their actions. However, if the 2 percent target is to be fulfilled, it is clear that stricter emission reductions relative to those indicated in the current NDCs are needed and transfers to vulnerable countries for adaptation should be realized.

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9 Conclusions and Further Research

9.1 Concluding remarks

The purpose of this volume is twofold:

1. To provide a review of the state-of-the-art of the economics of climate change.
2. To suggest that an important area of further research on the economics of climate change could be extended to monetary policy. This is because very little research has been undertaken in the area of climate change and monetary policy, and our approach seeks to explore ways in which monetary policy can help in the design of efficient climate policies.

With regard to the current state of the economics of climate change research, this volume begins, in Chapter 1, by establishing the context in which climate change economics has developed.

Chapter 2 presents the ways in which climate change after the industrial revolution is modelled. This is the period when anthropogenic emissions of greenhouse gases started to generate upward pressure on global and regional temperatures. This type of modeling is necessary in order to unify the economy and climate in a global model which can provide the links and the interactions between them and constitute the basis for the design of climate change policies.

Chapter 3 presents the way in which integrated assessment models (IAMs) model the economy and climate as coupled systems. IAMs have been both the main tool used in analyzing the impacts of climate change on the economy and also the basis for the design of climate policies. The most widely-used IAM, the Dynamic Integrated model of Climate and the Economy (DICE), is presented analytically. Then we review the new literature that focuses on environmental macroeconomics, which combines low-dimensional dynamic stochastic general equilibrium (DSGE) models with climate change. Finally, in this chapter there is a preliminary presentation of the role of the central bank under conditions of climate change.

Chapter 4 presents and analyzes one of the two main mitigation-related policies for climate change, which is carbon taxes. It includes an analysis of representative concentration pathways as predictors of climate change, as well as an analysis of carbon budgeting as a policy tool. The social cost of carbon (SCC) is a key parameter for the design of climate policy, and we thus present ways for calculating the SCC, along with examples of the limited application of carbon taxes and a brief presentation of carbon capture and storage, and deforestation reducing policies (REDD+).

Chapter 5 analyzes the other main mitigation-related policy, which is cap-and-trade policy. The chapter begins with the theoretical foundations of cap-and-trade policies. After a discussion of the basic model, issues of efficiency and market power are presented. Existing emission trading schemes (ETSs) are reviewed and evaluated – with an emphasis on the European Union Emissions Trading System – along with emerging ETSs in different parts of the world. Advantages and disadvantages of ETSs are discussed in light of the experience gained from their application. Finally, there is a discussion of taxes as compared to ETSs.

Chapter 6 presents and analyzes adaptation to climate change. In particular, the chapter reviews the economics of adaptation and private and public adaptation, along with the empirical methods for adaptation and, more specifically, the ways in which adaptation enters IAMs. Adaptation is also discussed at the global and sectoral levels. In addition, adaptation policy instruments and financial issues related to adaptation are reviewed.

Chapter 7 reviews some of the most important building blocks of joint models of the economy and climate. In particular, these elements include the social discount rate to be used in climate-related discounting, along with further extensions about gamma discounting and declining discount rates. The damage function – a central feature of IAMs – is reviewed, and alternative ways of modeling damages from climate change are presented. Risk and uncertainty, which is another major factor affecting climate change, is discussed, along with the impact of deep uncertainty in the design of climate policies. Finally, regional issues and the introduction of explicit spatiotemporal climate models – which bring economics closer to climate science – are presented.

Chapter 8 discusses the vital role of international cooperation in addressing climate change. The first part of the chapter focuses on the game theoretic basis of international environmental agreements. Issues related to the extension of the basic model which include heterogeneity, transfers and issue linkages are also reviewed. The second part of the chapter reviews the history of climate change negotiations, beginning with the First World Climate Conference in 1979 and continuing on through to the 2015 Paris Climate Conference (COP 21), highlighting the important provisions of the Kyoto Protocol and the Paris Agreement. The all-important role of the Intergovernmental Panel on Climate Change is also presented.

We believe that this comprehensive review of the economics of climate change not only provides an up-to-date presentation of the issues, but also provides a basis for the extensions and further research that are proposed in the following section.

9.2 Areas for future research

In the spirit of the new environmental macroeconomics, a promising area of future research could be the development of unified DSGE IAMs which include two interacting modules, the economy and climate. We envision such models having the following structure:

- In addition to 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 in chapters 2 and 3.
- 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, and help in the design of efficient adaptation strategies to mitigate the consequences of climate change.
- To give a real role to monetary policy, namely to make money matter to real variables, the research should follow the new-Keynesian tradition, and thus assume that product markets are not perfectly competitive and that prices are sticky, at least temporarily.
- The research will use and characterize feedback policy rules under climate change, and try to introduce new concepts such as the environmentally-adjusted output gap.

Thus, the main challenge will be to investigate the properties of central bank behavior and monetary policy under climate change and global warming.

The developed model could be calibrated to the US and/or the Eurozone and will explore the ways in which environmental risks in the form of shocks, and policy reactions to counter these shocks, affect the real economic activity and the environment. The basic questions that need to be answered include:

- Which potential monetary policy reactions associated with climate change are really stabilizing and which constitute unnecessary intervention?
- What trade-offs or social dilemmas are encountered in the use of monetary policy to address climate change issues?
- Can monetary policy promote adaptation, international cooperation and stable environmental agreements?
- What is the trade-off between fiscal tools (e.g., tradable permits or carbon taxes) and monetary tools (e.g., interest rates) in the design and implementation of climate change policies?
- What is the relation between mitigation and adaptation policies and the most desirable adaptation path?

The developed DSGE IAM model could be used to study small economies such as the Greek economy. The basic characteristic of small economies is that their GHG emissions are too small – relative to 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 evolve exogenously relative to the mitigation actions of small economies. The exogenous evolution of climate may have serious negative effects on these economies, as the recent study of the Bank of Greece (CCISC, 2011) revealed. It is therefore important to explore whether there is space for interventions on the part of the monetary authorities in order to mitigate the negative effects from climate change and support private and public adaptation, and to support technological transformations which are necessary under internationally-agreed-upon climate policies, such as the Paris Agreement and EU climate policies.

Finally, the role of the central bank should be explored in relation to the valuation of climate risks, stranded assets, and the potential differentiation between investments in 'green' or 'brown' sectors, given the increasing importance of these issues for the financial system.

Further extensions to the basic model could be directed toward addressing issues emerging from stochastic tipping points and spatial heat transfer, and focusing on climate change policy – including monetary policy – under deep uncertainty or ambiguity.

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