Advances of Climate Modelling for Policy Analysis

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ABSTRACT

This paper surveys recent advances in climate models by emphasising how quantitative instruments can answer the main crucial questions addressed by the policymakers involved and therefore aid the formulation of effective global climate policies. The limits of existing models are highlighted and new ideas and developments are shown to increase the reliability of climate models for policy analysis. It is also suggested that the complexity and uncertainties surrounding climate issues are difficult to translate into adequate policies without the help of sophisticated and integrated global quantitative modelling.

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1. INTRODUCTION

As global environmental changes and their related socio-economic impacts become ever more critical, any consequential international climate policy assumes increasing importance. Following the United Nations agreement to stabilise the world climate established within the Kyoto protocol in December 1997, national and international climate policies have become more significant than ever before. In most OECD countries, policy analysis of global climate change accounts for the results of large scale numerical models linking the economic, environmental and technological components in one advanced framework. The best example is the report prepared by the US Council of Economic Advisors, whose policy advice is largely based on analyses carried out using several climate models in which the economic dimension is integrated with the physical, biological and climatic ones. In Europe the situation is certainly less satisfactory. However, many EU governments and the EU commission are currently using quantitative tools to assess the effects of different policy options and particularly to quantify the costs of meeting the Kyoto targets.

The criticism usually raised against a quantitative approach to climate policy is based on the large uncertainties surrounding climate phenomena and the costs and benefits of mitigation options. This is largely due to the long-term features of these phenomena and to the complexity of the interactions between the cause, process, evolution, and impact of climate changes. However, these are also the main reasons that justify the use of a modelling approach to climate policy analysis. More than ever before, the issues and problems to be accounted for are so numerous, their links and feedbacks so articulated, that only a well-structured model can provide a comprehensive and coherent approach to the assessment and comparison of alternative policy options.

In recent years, various kinds of international and national climate models have been proposed. These models have different features and are often based on different methodological approaches. In this paper we would like to describe the main approaches to climate modelling and assess their recent advances, their increasing reliability and the remaining limits and drawbacks. To do that, we first identify some basic features of climate phenomena that constitute the peculiarities of the climate related methodological approaches and which the models used for policy analysis need to take into account. Then we give a brief description of the various kinds of national and international model approaches “traditionally” employed and finally highlight how the various issues stemming from an “optimal” analysis of climate changes have been tackled by the different models. The concluding section will provide some policy examples and identify directions of further research.

2. PECULIARITIES OF ECONOMIC-ENVIRONMENTAL MODELLING

The analysis of environmental phenomena and the assessment of reciprocal impacts between the environment and the economic system are characterised by some peculiar characteristics which imply a large number of challenging implications for investigation. Nevertheless, these peculiarities should be taken into account if the goal is a more realistic modelling approach. Besides the national dimension of the environmental problem, the international or even global dimension has to be incorporated, including a very long time horizon, the uncertainties of various factors and the irreversibility of some processes. From an economic perspective, a consideration of the dynamics of technical progress is essential in assessing the costs of policy measures, whereas the value of discount rates crucially affects the evaluation of any concrete future policy-related environmental benefits.

These are just some examples of factors which influence many environmental problems but that become basic peculiarities in the case of climate models. Indeed, in the case of climate phenomena, the time horizon can hardly be restricted to the short or medium term, given that most of the benefits of current mitigation strategies can be achieved only in the long-run. Nor can policy analysis be confined to domestic policies, given that these policies may be ineffective or even counterproductive without a common co-ordinated strategy at the global level. Uncertainties cannot be neglected, because they have a crucial influence on both the optimal timing and the geographical distribution of abatement options and their related costs.

In this section we analyse in more detail the peculiar features of climate-related phenomena, whereas the next section will discuss the ways in which the existing models are designed to handle these features.

Uncertainties

In spite of continuous scientific improvements the bio-physical aspects of a large number of environmental phenomena are still highly uncertain. This uncertainty increases with the spatial and temporal scale of the issue under investigation. The great scientific debate on the evolution of global temperature or on ozone depletion are just two examples of the still relevant role of uncertainty. Associated with this physical, chemical, and biological uncertainty, there is also an economic uncertainty which makes it difficult to evaluate the costs and benefits associated with environmental policy interventions.

Irreversibility

Natural phenomena do not generally follow linear evolutionary trends. Natural developments are characterised by radical changes that may dramatically modify living and economic conditions. As well as being non-linear, natural phenomena may also be “irreversible”. Once the point of no return is exceeded, changes are impossible to reverse: one dramatic example is the extinction of animal and vegetal species. Consequently, models need to be able to capture “jumps” and irreversibilities in order to predict and avoid dangerous divergence from equilibrium paths. Economic irreversibilities may also be relevant. Huge investments with long payback periods designed to reduce emissions may be difficult to modify in the light of new information. Development paths based on a given type of infrastructure are another good example of economic irreversibilities.

International dimension

As a result of their intrinsic physical characteristics, many pollution phenomena (e.g.: ozone depletion, global warming, acid rain, water pollution) necessarily involve more than one country. Yet in many other cases, even more limited environmental externalities, such as waste production, can defeat country borders due to the globalisation of economic markets and the related international flows of employment or capital. These are the so-called "leakage effects", which become very important in the case of climate changes because they affect both whether a coordinated policy strategy will be adopted and the environmental effectiveness of such a strategy when it is implemented.[1]

Moreover, accounting for the international dimension of climate problems requires consideration of the significant environmental, physical, economic and institutional differences between countries, such as the endowment and diffusion of technical progress, the nature of the leading sectors, etc. Accordingly, the different qualitative and quantitative degrees of environmental damage that could be experienced in different regions leads to the consideration of inter-country equity.

Spatial heterogeneity is thus a key question in designing an optimal, i.e. least-cost international climate policy. According to efficiency claims, the greatest efforts should be produced where abatement policies are less costly (or where benefits are higher). Hence, understanding "where" to act becomes crucial. Nevertheless, efficiency is not the only issue to be considered since, as mentioned, equity is equally important. Finding a "fair" balance between international equity and efficiency is one of the major tasks for policymakers and thus one of the answers most often sought from modelling.

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[1] Cf. Carraro and Siniscalco (1993).

The role of technical progress

Technical progress is a key variable influencing the relationship between any kind of human activity and the environment. This is true not only for the damage that production and consumption activities exert on the environment, but also for the ability of the economic and social system to bear and potentially correct these damages. To assess the benefits and costs of a given environmental target or to decide the optimal level of environmental protection, it is thus necessary to understand how, and to what extent, technical progress is able to promote a clean substitution between the environment and other capital goods. In most climate models, technological change is treated as "manna from heaven", whereas technological progress should be understood as an economic activity in itself, interdependent with the rest of the economy.

As improvements in technology are likely to lower the costs of pollution control, the modelling of technological progress is also relevant in influencing the temporal implementation of environmental policies. If technological change is viewed as driven by autonomous and unpredictable human activities, it could be better to postpone the intervention and await the endowment of the new technology; vice versa, if technological change is considered as dependent on past activities it could be more efficient to anticipate the intervention in order to stimulate the development and diffusion of new technologies.

Welfare

The ultimate task of an environmental-economic model is to define how private and social welfare are influenced when environmental externalities are accounted for and, accordingly, to evaluate an optimal (utility maximising) balance between the costs and benefits of environmental protection. Within an economic modelling framework, the determination of welfare depends mainly on indexes like the utility of discounted consumption, GDP or income distribution. But benefits also arise due to positive environmental changes and welfare calculation should therefore include secondary and non-market benefits and costs such as health benefits, or transport congestion, which are very difficult to measure.

Nevertheless the main controversy does not regard how to define benefits and include secondary benefits, but rather how to evaluate future costs and benefits, i.e. how to discount future welfare. The higher the discount rate, the greater will be the discrimination against future generations. As the cost of any present environmental intervention is borne by the current generation whereas the potential benefits will be experienced in the distant future, long term investigations implied by environmental analysis involve severe problems of intertemporal evaluation and intergenerational equity.

3. ECONOMIC -ENVIRONMENTAL MODELLING: THE DIFFERENT APPROACHES.

At the beginning of the 70s, the first environmental models tried to assess environmental impacts, mainly focusing on greenhouse gas (GHG) emissions. These models, usually built by natural scientists, were generally technical-climatic models rather than economic models, and were based on a small number of parameters and on qualitative/quantitative expert opinions.

Economists started to get involved in GHGs and environmental modelling in general at the end of the 70s. This kind of research was stimulated by the Toronto Climate Conference in 1988 which stressed the need to reduce CO_2 emissions to 20% below 1988 levels. As a consequence, climate modelling boomed, and a great number of regional and global works on the costs and benefits of CO_2 abatement appeared in journals and books.

In recent years, modelling techniques have changed. First, input-output and “macro-keynesian” models were replaced by Applied General Equilibrium Models, in part reflecting improvements in computer technology and algorithm solver methods. Subsequently, these model approaches were replaced by “eclectic” models with both “bottom-up” and “top-down” characteristics, which could also account for the possibility of temporary disequilibria in factor markets. Currently, with the so-called Integrated Assessment Models (IAMs), environmental modelling aims to amalgamate the knowledge from different scientific fields – economics, bio-geo-physics, engineering, demography, etc. – in order to tackle the environmental issue in the most comprehensive possible way.

In this section we would like to present these different modelling approaches and highlight the methodological advances achieved by the recent economic/environmental literature.

3.1. «Bottom-up» models

In order to get detailed information about the techniques, structural effects and sectoral behaviour of an economy, so-called “bottom-up” models are employed. These partial equilibrium economic models describe the economy from the “bottom” side and emphasise the “green” potential of available technologies. They can be classified into technical supply and demand models, or organised into linear or non-linear system optimisation models, system simulation models and partial forecast models. As an outcome, “bottom-up” models can show marginal abatement costs and the so-called “no-regret” possibilities, i.e. energy saving possibilities without high costs. A good example is the ETSAP[2] model. MESSAGE III, used at IIASA, is another “bottom-up” model which also accounts for uncertainty about future growth paths as well as the possibility of endogenising technical progress.[3]

The macroeconomic and more “top-down” view of the economic system is generally assumed to be exogenous, but the results of “bottom-up” models can be used as an input in macroeconomic models (a so-called “soft-link”), as in the model MARKAL-MACRO[4]. MARKAL is a national system optimisation model which determines the best, i.e. cost-effective, energy technology solution and provides marginal abatement costs, energy prices and rate of technical change as an input for MACRO, a simple production and utility function for the total economy.[5]

The main limit of the “bottom-up” approach is that it generally neglects feedbacks in the economy and rebound effects on international energy markets. Moreover, it does not account for the uncertainty concerning many environmental phenomena, the actual diffusion process of new technologies, and the effects of environmental policies. Finally, it generally cannot be used to provide an estimate of the costs of reducing GHGs on a global scale.[6]

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[2] See Kram (1994).
[3] See Messner, S. and Strubegger, M. (1994).
[4] See Kypreos (1997).
[5] See Manne, A.and Wene, C.-O. (1994).
[6] See Wilson and Swisher (1993).

3.2. «Top-down» models

Input/Output (I/O) models

Input/Output models are based on national input/output tables and can be used to compute many of the direct and indirect effects of mitigation policies. Input/output tables can also be used to demonstrate the direct and indirect relations of energy or environmental goods or sectors. Within a static framework, I/O models cannot show the intertemporal and dynamic effects of investment changes; dynamic I/O models, however, include the effects due to investment changes over time. Additionally, traditional dynamic input/output analysis can be enlarged to include a production function with substitution effects instead of a (Leontief) production function in order, on the one hand, to account for the so-called AEEI factor (autonomous energy efficiency improvement) illustrating technological progress, and on the other, to present intersectoral substitution effects due to relative price changes.[7] By including flexible exchange rates, international trade relations can also be simulated. This approach can demonstrate all direct and indirect economic effects such as structural effects, as well as international factor flows. However, I/O models are mostly developed to examine the final demand side effects at a national level, for example, to investigate the intersectoral effects of a change in government or consumption expenditures.

Macro-econometric models

In principle, econometric models could be based on several different economic theories. However, most econometric models used for environmental analyses can be considered “neo-Keynesian” in the sense that the economic system is demand-driven. Initially developed as pure economic models, they were adapted to investigate the climate change issue by introducing energy among the traditional production factors in the production function or in the firm cost function, in order to determine energy demand.

In most cases, macroeconometric models are based on long run time series data which are not always available for environmental goods and sectors. In general, econometric models are highly flexible, providing answers to many kind of economic questions. They can include

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[7] See Kemfert and Kuckshinrichs (1997).

macroeconomic approaches in combination with environmental submodels. Econometric models can also be based on national input/output tables with all information about direct and indirect sectoral relations. Generally, econometric models are used as economic evaluation and forecasting tools, whereas input/output models and CGE models in particular are used in simulations, analysing “if-then” processes. Because of data constraints, macroeconometric models are mainly used for national questions but can be enlarged for multi-national dimensions. Because of their structural features, they are generally used for short/medium run analyses.

General equilibrium models (GEMs)

General equilibrium models follow a neoclassical or “Walrasian” view of the economic system, describing the total economy through the behaviour of optimising producers and households which demand and supply goods and factors. Adjustment processes to excess demand and supply determine equilibrium prices in all markets. Profit maximisation under perfect competition and free market entrance guarantee zero profits and the optimal distribution of resources.

Mainly, GEM models use non–linear substitution-based production functions of the CES type (Constant Elasticity of Substitution) to describe production behaviour and the same type of functions to describe the consumption behaviour of economic agents. If CES production functions also include energy as a primary input factor, autonomous assumptions about all substitution parameters have to be made for all inputs. Furthermore, a so-called autonomous energy efficiency improvement factor (AEEI) is often used to describe the energy efficiency progress autonomously, i.e. no endogenous determination of technical improvement is included. Dynamic processes are included either by so-called recursive-dynamic models determining temporary equilibria under myopic expectations, i.e. by considering capital or investment in the last period; new capital or investment is calculated for each other period. Intertemporal GEMs determine capital or investment changes due to endogenous growth rates without temporary equilibria.

GEMs are able to describe the national economy as well as complex international relations and furthermore are able to calculate all “feedback-effects”, i.e. quantity effects due to price changes and vice versa. However, general equilibrium models describe the economy by finding an equilibrium price in each market which clears perfectly. This is unrealistic, especially for the labour market, which can hardly be considered in equilibrium in most countries. For equilibrium models it is thus necessary to enlarge the model structure to account for imperfect markets and incomplete information. Based on a national input/output table, GEMs are mainly used for national policy analysis. However, there are example of GEMs, like GEM E3 or LEAN[8], designed for the European Union and, as in the case of GREEN, for the world economy.[9] When general equilibrium models are based on a multi-national framework, they can be used to simulate the effects of various environmental strategies such as emission trading and international emission taxes.[10]

«Second generation» models

Given the above limitations, in the early 90s some models were developed which share the structure of GEMs but try to attain greater correspondence with reality. These models abandoned perfect competition in factor markets, especially in energy and labour markets, including the possibility of endogenising technical progress, generally by means of the construction of an index of the «quality» of capital, directly dependent on energy prices. More sophisticated approaches are melting «top-down» models, driven by agents’ behaviour, with «bottom-up» and I/O models in a so-called «soft-link», i.e. disaggregated sectoral analysis and detailed description of energy sectors.[11]

These models suffer from one specific limitation: given the high detail of the analysis they generally involve a great number of equations and endogenous variables, resulting in very complicated computational problems[12]. Examples of sophisticated econometric model

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[8] See Capros et al. (1995) for GEM E3 and Kemfert and Welsch (1998) for LEAN. Another model is Boehringer et al. (1997).

[9] See Burniaux et al. (1992).

[10] See Conrad, K. and Wang, J. (1993) and Boehringer, C., Harrison, G. and Rutherford, T.(1997).

[11] See Boehringer et al. (1997).

[12] Higher detail is not always a guarantee of better analysis: sometimes simpler models are better able to capture the fundamental economic feedbacks than larger and more complex models.

approaches are the WARM[13] and the E3 ME[14] models used for European analysis. In the US, some features of MERGE and SGM can be considered as good examples of the recent evolution of climate models and of their ability to combine a top-down representation of the economy with a bottom-up description of technology in energy markets.

3.3. Integrated Assessment

Integrated Assessment (IA) is a process aimed at combining, interpreting and communicating knowledge from diverse scientific fields in order to tackle an environmental problem comprehensively by stressing its cause-effect links in their entirety. The primary strength of IA is its multi-disciplinarity, allowing the definition of the issue under investigation widely and precisely and - according to the available knowledge - to reduce the degree of uncertainty or to incorporate uncertainty aspects into the analysis.

It is worth saying that another major task of IA is to improve relationships between the scientific and the political field. This goal should be accomplished by providing more reliable, transparent and precise results and by designing the policy process in such a way as to increase interaction between researchers, policymakers and the main stakeholders

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[13] See Carraro and Galeotti (1996).
[14] See Barker and Zagame (1995).

Integrated assessment models

Recently, so-called “Integrated Assessment Models” (IAMs) have been used to describe intertemporal optimisation decisions, combining this with environmental or climate change sub-models. IAMs, often applied in global economic and environmental simulations, can incorporate uncertainties and risk analysis, calculating costs and benefits of environmental policy. IAMs generally contain a production function approach comprised of capital, labour and energy and a so-called “Hicks-neutral” technical progress factor (AEEI). Up till now, the majority of IAMs have not taken account of endogenous technical changes. From their theoretical approach, IAMs maximise discounted intertemporal utility of a representative agent subject to the budget constraint. The social rate of time preference lies mostly in the area of 3 %.

Three categories of IAMs can be identified: models which state the effect of anthropogenic activities on the environment; models which state the effect of anthropogenic activities on the environment and the related feedbacks in term of human health; and models which try to assess the anthropogenic effects of human activities on the environment and the related feedbacks in term of market and non-market costs and benefits. In the first two cases, the models are strongly “environment-oriented”, whereas in the latter, the environmental and the economic parts have equal balance and importance. In fact, cost-benefit analysis requires an accurate definition of the environmental system coupled with a detailed description of the functioning of the economic system and of the linkages between the two.

These last “economic” IAMs are and have been used both for simulation and for optimisation. Nevertheless, they maintain an “optimising perspective” (they answer the question of how to obtain a desired result in the most efficient way) from which “pure” *optimisation models* and *evaluation models* have developed.

The perspective of an optimisation model is to define the optimal level of environmental externality sustainable by the economic-environmental system, for example how much polluting emissions can be put in the atmosphere or how much acid rain can be tolerated, etc.

Indeed, the “philosophy” of evaluation models is to assess the optimal path to accomplish a given environmental target.

In dealing with IAMs some considerations should be taken into account:

1- Every integrated assessment analysis is no stronger than the underlying natural and economic science on which it relies;

2- Uncertainty still plays a great role. The direct consequence is that it is difficult to choose one policy in preference to others based on current knowledge about the climate system and human interactions with it. Thus research aimed at stating the various “uncertainty effects” (effects on natural variables forecasts, effects of the propagation of uncertainty among natural and economical variables, effects on policy options) are crucial to improve IA;

3- The issue of endogenous technical progress is still largely unexplored;

4- Most current models do not well match the social and economic organisation of developing economies. This fact can lead to biases in global assessments when impacts in the developing countries are evaluated as if their economies operated like those of developed countries.

4 PECULIARITIES OF THE ECONOMIC-ENVIRONMENTAL MODELLING: ANSWERS FROM THE DIFFERENT APPROACHES

4.1. Uncertainty and Irreversibility

Given the relevance for scientists and policy makers of uncertainties about both future climate change as well as the benefits and costs of slowing it, various models have been designed with the specific aim of defining the "cost" of this uncertainty. A "common" approach is to quantify the value of "early knowledge", that is, the economic value of resolving the uncertainties about climate change sooner rather than later. Nordhaus and Popp,[15] using the PRICE model, a probabilistic version of DICE obtained by the Monte Carlo technique, sampling over all possible future scenarios, first define a learn-then-act framework, corresponding to a perfect information situation. Then, to model the effects of learning, an act-then-learn scenario is built that breaks simulation time into three phases: (1) the first period, in which agents - who do not know which state of the world they are in - maximise expected value of utility. Given their imperfect information they have to take all the possible different distributions of economic and geophysical parameters into account, (2) the second, when, at some future date, uncertainty is resolved, i.e. the true value of parameters become known, (3) the third, represented by all subsequent periods, when agents act with perfect information about the state of the world. Finally the value of information (the "cost" of uncertainty) is calculated as the difference between the expected value of net damages with "good" information (learn-then-act case) and that with poor information (act-then-learn). The approach of Nordhaus and Popp allows an estimate of the value of information not only about different "states of the world", but also about individual variables and about different modelling areas (environmental, socio-economic, technological etc.). According to this study the value of anticipating knowledge by 50 years ranges from $45 to $108 billion.

A similar method is used by Manne[16], who analyses the value of information about two key parameters – climate sensitivity and warming damage – using seven different IAMs (CETA, DIAM, DICE, HCRA, MERGE, SLICE, Yohe). The value of the information highlighted is

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[15] See Nordhaus and Popp (1997).

[16] See Manne (1996b).

"low": it is close to $100 billion, but only when the probability associated with the different values of the key parameters is close to 50% - otherwise it falls rapidly to zero.

A different perspective in accounting for uncertainty is the direct possibility offered by some models to evaluate the outcome of a given action under different future (more or less likely) scenarios which could be chosen by the user. Models like FUND, PAGE, ICAM and Yohe (CONNECTICUT) belong to this category.

FUND is an integrated assessment model of climate change. Essentially, it consists of a set of exogenous scenarios and endogenous perturbations, specified for nine major world regions. The exogenous scenarios concern the rate of economic growth, the share of agriculture in Gross Regional Product, population growth, Autonomous Energy Efficiency Improvements, the rate of decarbonisation of energy use, and methane and nitrous oxide emissions.

PAGE is a probabilistic "policy-oriented" model which allows an interesting analysis of uncertainty specification and propagation: all majors parameters on the emissions, atmospheric, climate and impact side are represented by triangular probability distributions whose parameters can be set by the user.

The ICAM model versions are designed to capture the uncertainties in knowledge about the precursors, processes and consequences of climate change. The models can be used to simulate abatement activities, adaptation to a changed climate, and geo-engineering activities. ICAM has been used to show the wide range of possible future emissions, climate conditions and impacts and the dangers of deterministic models with narrow sensitivity studies, the importance of aerosol forcing in regional policy decision-making and the relative importance of decision rules in policy decision making. Illustrative runs of ICAM show how uncertainty confounds the choice of GHGs abatement policies and how key factors in determining the character of the problem and key uncertainties in making informed judgements can be identified.

The Yohe (CONNECTICUT) model was explicitly designed to accommodate quick analyses of a wide range of global mitigation policies in the context of uncertainty about economic, demographic, and natural scientific parameters. The model depicts global economic activity as a function of labour and fossil/non-fossil fuel, and it determines the consumption of energy according to least cost principles. Alternative assumptions about elasticities of substitution between the two types of fuel and between energy *per se* and labour can be accommodated. Alternative assumptions can be employed with regard to neutral technical change in the production process, the rate of population growth, the rate of technological change in the supply of both types of fuel, the long term availability of fossil fuel, the carbon content of those resources, the degree to which growing scarcity is reflected over time in the market price of fossil fuel and the degree to which changes in global mean temperature affect economic activity.

Finally, a third approach to uncertainty is to describe how an uncertain, but possible, future and irreversible event can influence present decisions. Such a study has been performed by Gjerde et al. (1998), who introduce the probability of a catastrophe in an IAM similar to DICE. In each time period the utility function (the objective function) is the weighted sum of the utility in the case that a catastrophe occurs and the utility in the case that it does not. The weights are given by a factor, which represents the "survivor rate". The survivor rate decreases as global warming increases (the probability of a catastrophe increases), thus reducing overall utility. The research confirms that accounting for uncertain irreversibility makes it optimal to increase the environmental protection effort.

4.2. Technical progress

"Bottom-up" models couple a detailed description of present technological opportunities with a completely exogenous representation of future trends in technical progress. Generally they do not take into account either market dynamics in energy sectors or the feedbacks of technological choices in the economic system. Moreover, they assume as given the existence of factor substitution technological opportunities which lower the relevance of impacts deriving from increasing energy prices. Thus they tend to overestimate the substitution possibilities in the economy: in fact different technologies could be feasible from a technical but not from an economical point of view. As a consequence, they may remain “out-of-the-market” altogether or may not be widely diffused within it.

Most “top-down” models introduce a time trend as a proxy for technical change. In this respect, Jorgenson and Wilcoxen’s treatment of this variable is original[17]. Their model assumes a translog unit cost function containing terms in which the input prices interact with the time trend. Firms' cost trends therefore depend on input prices and on the time trend. Finally, technical progress influences input demands, without interacting with any other variable. Thus policy decisions affecting relative prices determine an endogenous change in total factor productivity, and this partially endogenises technical progress.

A more satisfactory treatment of technical progress relies on the concept of vintage capital followed in the OECD's GREEN model. Here the substitution possibilities are more feasible with the most recent capital vintages. Thus, adjusting to relative price shocks depends not only on the elasticity of substitution but also on the capital replacement rate. This is a novelty with respect to previous CGE modelling approaches because technical change shows its effects on the firms' cost structure through a parametrisation of each vintage's cost functions. Models using the idea of capital vintages have some drawbacks too, because they do not provide a precise evaluation of the mechanisms through which markets and agents act to modify the existing technologies towards energy saving and environmental potentials: the mere existence of new, less polluting technology does not imply that it will be adopted by firms.

Although technological progress cannot be observed, its dynamics can be inferred by looking at the dynamics of factor demand which depends upon the dynamics of technical progress (latent variable approach). In the formulation proposed in the GEM model, the variable representing technical progress depends on the relative price of energy and on relative production in the manufacturing sector, which are endogenous variables, determined by the other equations of the model, and which in turn depend on factors such as policy decisions to mitigate greenhouse gases.

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[17] See Jorgenson, Wilcoxen (1993).

Another econometric model, WARM, designed for the EU[18], attempts to provide a more explicit description of the economic mechanism through which economic variables affect technical progress. Again, the basic idea is that technical progress cannot be observed and that it must be inferred by observing the dynamics of other variables. However, the focus is now on the capital stock. It is assumed that the capital stock can be broken down into two parts, the energy-saving/environment-friendly capital stock and the energy consuming one. Each year a new vintage of the capital stock becomes operational, i.e. new capital is added to the two components. The equations defining the rate of growth of the different kinds of capital are first estimated using the Kalman filter, then an indicator of environmental technical progress, which can be interpreted as an indicator of the environmental quality of the capital stock, given by the ratio between environmentally friendly and polluting capital. The dynamics of this indicator generally affects the economic agents' optimal decision rules. An increase in R&D expenditure by firms can increase the technological possibilities of the economic system which are likely to produce investments in environment-friendly capital. The amount of R&D depends on policy variables such as environmental taxation and innovation subsidies, relative prices, sales, and other endogenous economic variables. The qualitative change in capital induced by R&D and innovation thus corresponds to a qualitative change in production technology. New complementarity forms between the variable inputs and capital; new substitutability relationships among inputs become possible.

Given the computational and structural difficulties in transposing the above solutions to an optimising framework, endogenising technical progress is still at an early stage in Integrated Assessment Models. As mentioned, most of them represent technical improvement as a change in AEEI, the autonomous energy efficiency improvement[19], which should capture any exogenous technical change that results in higher levels of energy efficiency. Within this context, some models are exceptions. The IA models CETA and MERGE consider different electric and non-electric energy technologies entering and exiting the market according to quantity and price constraints. Thus even if AEEI is exogenously given, it is the price mechanism that determines the production technology used. This is the so-called “back-stop” approach: certain technologies are available, but remain economically unfeasible because they

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[18] See section 3.2.

[19] See section 3.2. *GEM.*

include the costs of engaging in R&D. They enter the market only once the price of "old" technologies increases in response to the increasing scarcity of their base resources.

Dowlatabady and Orawitz[20] have estimated the relationship between the observed AEEI and energy prices and have then implemented this relationship in their ICAM 3 model so that each variation in prices is directly reflected in a variation in AEEI. In R&DICE, Nordhaus[21] tries to define how technological innovation reacts endogenously to price variations. This result is accomplished by adding an energy/carbon input, which depends on energy prices, to the DICE Cobb-Douglas production function. Then he performs simulations, including carbon taxes, which increase energy prices. Thus the model determines, along with the "optimal" level of carbon taxes, the level of R&D in the energy/carbon sector which optimises world income. The carbon tax is the policy variable and R&D reacts to maximise private profits. A major limitation of all these approaches is that they fail to consider innovation which is not induced by prices.

4.3. International dimension

As already mentioned, economic models applied to the analysis of climate change vary in their level of geographical disaggregation. Integrated Assessment Models investigate climate change and its impact on the world economy at a global and international level. In general, a higher level of aggregation results in higher estimates of both the costs of damage as well as the benefits due to environmental improvements. Furthermore, a high level of geographical aggregation requires more exogenous information, such as parameter sets, and is not able to include significant characteristics of regional market structures and interrelations. On the contrary, disaggregated models, such as "bottom–up" models, investigate environmental impacts at a detailed national level. In particular a better representation of disaggregated household or firm behaviour is achieved by input-output models, Applied General Equilibrium Models and econometric models.

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[20] See Dowlatabady and Orawitz (1997).
[21] See Nordhaus (1997).

In addition, macro-econometric and CGE/AGE models have been widely used for international analyses at a continental or even global scale. Generally, the international linkages are given by foreign trade flows (only C-CUBED also includes capital flows), thus enabling macro-econometric and CGE/AGE models to capture economic “leakage effects”. In fact, as the domestic goods and services produced within a country become more costly in response to measures of environmental protection (since they are charged with the “price of the environment used during their production” by means of taxes, regulations, etc.), these models allow for the switching of world demand towards less costly goods and services produced in countries with less stringent environmental standards. As a consequence, pollution in those countries tends to increase. Models such as GREEN, GEM-E3, QUEST, and virtually all kinds of the international models mentioned above, highlight the “leakage” which results in the case of unilateral or non-global intervention for environmental protection. However, the international dimension of environmental externalities captured by this approach is limited to the quantification of the potential change in the emission patterns of other countries which are induced when countries adopt a particular “environmental friendly” strategy.

If this is a crucial first step in, for example, the evaluation of the effectiveness and efficiency of an international “green” agreement, it nevertheless fails to tackle two other relevant features of the international scope of environmental phenomena: firstly, the fact that the global environmental externality is likely to exert a feedback on the economic system, affecting the economic decisions of households and firms (in other words, their welfare) and that this feedback is necessarily influenced by country-specific economic factors; secondly, that the physical environmental impacts are also highly differentiated among countries.

These two issues are specifically investigated by those IAMs which split the world into macro regions. With regard to the first aspect (the different impact on welfare of a given environmental externality) IAMs incorporate a functional relationship in the welfare functions which accounts for the negative effect of environmental damage and of the costs of environmental protection on agents’ utility, usually represented by per-capita consumption. Given the two different costs, these models are able to find the “optimal” balance between the two. Environmental feedbacks on utility are calculated by a damage/benefit function which translates world temperature changes (which depend on overall emissions) into terms of GDP losses. Country specificities are thus accounted for through two channels: the key parameters of the production functions (which in turn define consumption) are differentiated among regions; moreover, the utility functions of different countries are weighted with country (and time)-specific weights, which are supposed to assess the different "perception" of utility changes. This approach is followed by models like RICE, MERGE, FUND, IIAM.

With regard to the second topic (the different physical impacts), some IAMs incorporate a "distributive" module in their environmental module which takes into account the fact that the increase in world temperature (and therefore in damages) is highly non-homogeneous at different latitudes. PAGE95, for example, includes in its analysis the changes in regional temperature which result from the effect of sulphate aerosol on radiative forcing which has a "typical" regional relevance. The ESCAPE model includes a specific module - CLIMAPS - which uses the global mean temperature projections from other submodels to construct regional climate scenarios.

Given these "regionalised" characteristics, IAMs are particularly suited to evaluate the possible outcomes of different options of internationally coordinated actions to cope with the environmental issue. They measure firstly, how pollution control (generally represented by different emission stabilisation targets) in a country or group of countries would be translated into an increase in pollution outside this area, and secondly, how its costs and benefits would be distributed among different regions. This provides a useful framework for deciding where and when to act and how to design proper compensations in order to find a "fair balance" between efficiency and equity. After the 1997 Kyoto meeting on climate change, a lot of recent modelling efforts have been devoted to defining the emission trading system proposed by that protocol. The results, as shown in the EMF16 report by the Energy Modelling Forum of Stanford, are very interesting because they highlight a great degree of convergence among the different models. In particular, one basic conclusion emerges from the report. All models predict that the cost of meeting the Kyoto target can be largely reduced if a system of emission permits is implemented (with respect to the case in which only domestic measures are adopted).

4.4. Welfare

In economic models which evaluate the impacts of climate change, welfare is mainly represented by indices such as discounted utility or GDP. The benefits of environmental changes are calculated in terms of increases of GDP or utility, despite the fact that GDP is not a sufficient welfare index since it fails to consider both the secondary benefits of environmental protection, such as an increase in health, and positive external effects, such as an improvement in urban air quality. For example, economic models which focus on a disaggregated national analysis, such as GEM E3 or WARM, can only compute welfare in terms of economic costs or consumers' utility, thus neglecting environmental benefits.

Integrated assessment models maximise utility over time, thus determining the costs and benefits of emissions reduction in terms of GDP. Most of them are structured in a way that considers a representative consumer as one who maximises discounted intertemporal utility, subject to a budget constraint. Usually a single production sector is considered, where output is determined by the technical relationship between capital, labour and energy inputs. Within this framework, welfare is once again represented by the maximised intertemporal utility function, but in a novel fashion, IAMs explicitly account directly in the utility function of economic agents for the environmental primary benefits accomplished. One exception is the IAM model FUND which also includes non-market damages because it explicitly considers the impact of global warming on human health (the increase in deaths due to heat stress), on quality of life (migrations) and on other non-market values (loss of biodiversity).

As we have said, with regard to welfare calculations, the choice of method of discounting future costs and benefits is controversial, i.e. according to the «prescriptive» or to the «descriptive» interpretation of the discount rate. The time preference included in economic investigations accounts for the fact that people prefer their benefits sooner rather than later, therefore suggesting a high discount rate. The higher the rate of discount, the greater will be the discrimination against future generations. However, the «prescriptive» determination of the discount or time preference rate calls for the inclusion of an ethical judgement concerning the welfare of future generations, i.e. that the time preference rate should be as low as possible. Most IAM models use the «descriptive» time preference rate of about 3%, as in the case of MERGE, RICE and PRICE. This is also due to the mathematical structure of IAMs in which a low discount rate leads to an excessive increase in investment, creating results that cannot be considered plausible, as shown for example by MERGE.[22]

More research is therefore necessary to improve our assessment of the optimal discount rate. More research is also needed in general to achieve a better measurement of social welfare which accounts for both the economic and environmental, and the direct and indirect, benefits and costs.

4.5 Summary

Table 1 provides a classification of the best-known and used applied environmental-economy models. They are classified according to their national, European or international dimension, their "bottom-up" linear or non-linear programming (LP or NL) nature, or their "top-down" input/output (I/O), macro-econometric, general equilibrium (GEM) or Integrated Assessment framework. Albeit incomplete, this table should aid comparison of the different available models while presenting a rapid overview of their main features.

It is clear from Table 1 that recent advances in climate modelling have moved towards global, regionalised Integrated Assessment Models with a clear microeconomic structure derived from a general equilibrium framework. In these models, the long-term dimension of climate

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[22] See Manne (1996a).

problems, the uncertainty surrounding climate phenomena and their impacts, the role of economic and technological mitigation policies are accounted for, and more reliable results are therefore being obtained, thus providing increasing support to the design of climate policies.

Table 1: Climate models. A taxonomy.[23]

	National	EU	Global	Global-regionalised
Input/Output Models	MIS MEPA			
LP / NLP Models	MARKAL ETSAP MESSAGE III	HERMES-MIDAS MARKAL		IEA (10 world regions) MARKAL
IA Models		ESCAPE *	DICE,R&DICE,PRICE SLICE CETA Yohe Gjerde et.al	IMAGE 2.0 (13 world regions) RICE (6 world regions) FUND (9 world regions) PAGE (4 world regions) MERGE 3 (5 world regions) IIAM (26 world regions) ICAM (7 world regions) MINICAM (9 world reg.)
CGE/AGE Models	Conrad (D) Bovemberg-Goulder (USA) Jorgenson-Wilcoxen (USA)	GEME3 Boehringer et.al. LEAN		ERM (9 world regions) EPPA (12 world regions) SGM (20 world regions) GREEN (12 world regions) G-CUBED (8 world regions) Whalley-Wigle (6 world regions)
Econometric Models	MDM (UK)	QUEST WARM E3 ME		WORLDSCAN POLE

* ESCAPE is used for integrated assessment analysis at the European level, even if it is based on the results of global disaggregated submodels as IMAGE.

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[23] See Manne, A. and Richels, R. (1992): MERGE2, Nordhaus, W. (1993): DICE, Peck, S. and Teisberg, T. (1992): CETA; Barns et al. (1992) ERM; CEC (1991): QUEST; Nordhaus, W.D. and Yang, Z. (1996): RICE; Barker T. (1994): MDM; Barker, T. and Zagame (1995) E3ME; Rotmans et al. (1994): ESCAPE; Rotmans J. (1990): IMAGE; Alcamo (1994): IMAGE 2.0; Capros, P and Karadeloglou, P. (1992) HERMES/MIDAS; Tol, R. (1997) FUND; Bernstein et al. (1997): IIAM; Dowlatabady, H. and Kandlikar, M. (1995) ICAM; Hope et al. (1993): PAGE and Rowe, M.D. and Hill, D. (1989):IEA, Gjerde et al. (1998); McKibbin and Wilcoxen (1995):G-Cubed; Fisher-Vaden et al.(1993): SGM; Yang et al (1996): EPPA; Edmonds et al. (1996): MINICAM; Kolstad, C. (1994): SLICE.

5 CONCLUSIONS

Many of the actions currently being discussed in fora around the world to counter the perceived threat posed by climate change depend heavily on policies and policy instruments designed to curb emission levels, many of them framed within broader industrial, environmental and energy policies. The complexity of policy design required when dealing with climate issues, and the uncertainty surrounding these issues, call for a comprehensive and articulated policy framework in which learning about the causes and effects of climate changes and about policy options and processes is coupled with adequate mitigation and adaptation strategies.

The role of economic-environmental modelling in this framework is crucial. It provides a link between “hard science” and “soft science”, by fostering communication and by providing results that quantify the costs and benefits of the phenomena identified by “hard sciences”. These costs and benefits are the crucial information that enables policymakers to take adequate policy options. Increased communication among the researchers involved in integrated modelling of the type described in sections 3 and 4 has already achieved new important results that enhance the reliability of policy analyses carried out with these models. More progress is still needed. For example, in the sphere of physical models of climate, the actors involved in the evolution of mitigation and adaptation strategies would benefit enormously if consideration of their needs led to a shift in the balance of modelling activity towards the development of models with a greater short-term predictive capability**.**

One could react to the above statements by arguing that the real issue does not regard the causes and effects of climate changes and the consequent policy actions to be undertaken, but rather whether climate changes are actually under way. If no climate change is detected, the above modelling and policy efforts may be meaningless.

However, in dealing with climate change, the key issue is our **uncertainty** with regard to the true nature and extent of the threat posed by climate change and our **limited understanding** of how to deal with it. The most important priority, therefore, is to rectify this situation, which means an extraordinary investment in learning-oriented research geared towards understanding both the dimension of the climate change problem and our ability to respond to it.

For these reasons, investment in integrated assessment global modelling of climate changes has a strategic nature. It is the means by which all aspects of this complex phenomenon can be assessed as a united whole; it provides the crucial information required by national policymakers in negotiating the targets, burden-sharing and implementation of cost-effective policy instruments; it aids quantification of the costs and benefits of alternative policy options that can be related to societal priorities in the allocation of public and private funds.

Are integrated assessment climate models ready to provide the type of knowledge and policy support just described? The answer is obviously negative. Many questions still remain unanswered, on both the economic and bio-physical side. However, many research teams are moving in these directions, in both the US and the EU. The recent creation of the European Forum for Integrated Environmental Assessment Models is an important step in the direction of fostering research on these models in the EU. An increased Italian contribution to this research process is crucial.

This paper has outlined some of the limits of existing climate models and described the advances achieved by Integrated Assessment Models of climate. Nevertheless, further research is necessary on all the issues addressed by this paper. From uncertainty to technical change, from market imperfections to welfare analysis, scientists and economists must unite their efforts in order to provide policymakers with effective and reliable policy scenarios.

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