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Integrated Impact Assessment Models of Climate Change with an Emphasis on Damage Functions: a Literature Review

Ramon Arigoni Ortiz and Anil Markandya[1]

We review the literature on the impact assessment models currently used in the climate change debate. From among these we select some relevant models, highlight their important features and identify how climate change damages are treated. A common feature of the treatment of climate change damages within the existing models seems to be the significant degree of subjectivity involved in the choice of parameters, functional forms and the potential damages in case of temperature changes above the current predicted (low) levels. This is in part due to the small number of studies available from which we can estimate climate change damages. It forces researchers to extrapolate, from a small set of figures, damages for higher temperature changes and for regions of the world other than those where the original studies were undertaken. Thus, uncertainty surrounding damage functions is inevitably high.

Keywords: Climate change, Integrated Impact Assessment Model (IAM), damage function

JEL Classification: C60, C68, Q54

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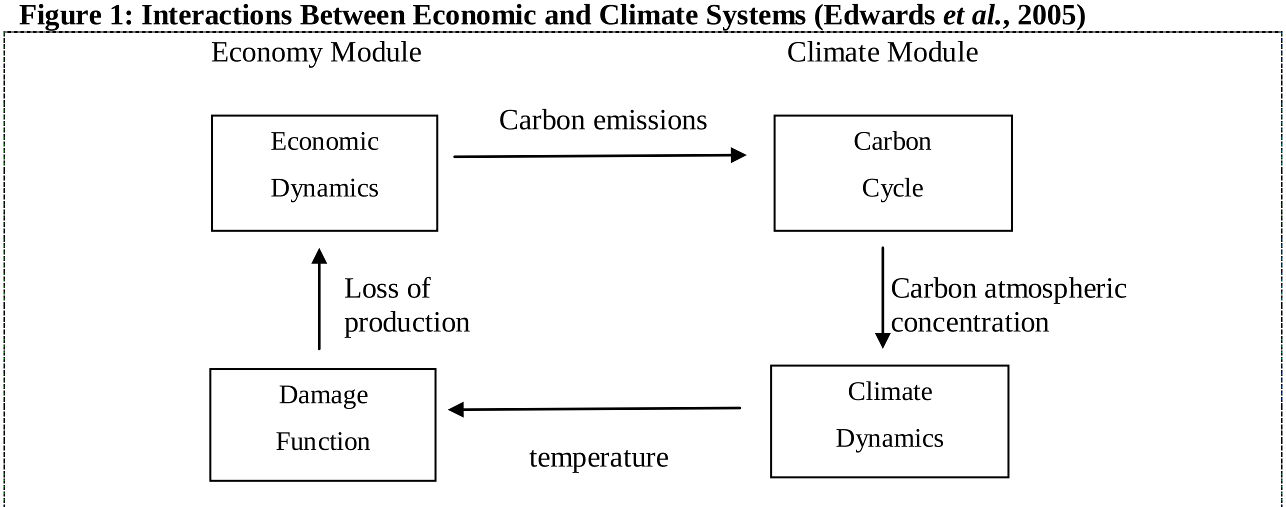
1 Introduction

By definition, integrated assessments seek to understand the linkages or interactions and feedbacks among complex systems. Integrated Impact Assessment models (IAMs) of climate change are motivated by the need to balance the dynamics of carbon accumulation in the atmosphere and the dynamics of de-carbonization of the economy (Nordhaus, 1994). An example of the interaction between the economy and climate systems is shown in Figure 1. IAMs have become recognized instruments for policy makers providing useful information and scientific insights for climate policy. These models can be classified in a number of ways. For example, Toth (2005) divide them into (i) policy evaluation models and (ii) policy optimization models. The first group is formed by simulation models that take user-defined assumptions about a course of future policy and calculate the implications of the specified policy for all modelled variables of interest of the policy-maker (e.g. temperature change, ecosystem and agricultural yield changes, sea-level rise). Policy optimization models summarize the relevant boundary conditions in a set of defined parameters in a scenario, separate key policy variables that control the evolution of the climate change problem (e.g. GHG emissions, carbon taxes) and determine the value of these policy variables in an optimization procedure. Stanton *et al.* (2008) separate IAMs into (i) welfare optimization models – models that maximise net present value of utility of consumption subject to climate change damages and abatement strategies; (ii) general equilibrium models – models that represent the economy as a set of linked demand and supply functions for each economy sector; (iii) simulation models – those based on exogenous scenarios about future emissions and climate conditions; and (iv) cost minimization models – models that identify the most cost-effective to a climate-economics model. However, most classifications of IAMs found in the literature allow for some overlap between sub-groups of IAMs, since there are models that fit into more than one classification.

Figure 1: Interactions Between Economic and Climate Systems (Edwards *et al.*, 2005)



We group the existing models used in the climate change debate in a different way: we split the economy module into three distinct sub-modules that better separate the models according to the emphasis they put on different aspects of the economy. These sub-modules are (i) the economic dynamics or economic growth module, in general represented by an applied or computable general equilibrium model (CGE) of the global (or regional) economy; (ii) the energy module, in most models constructed in a

´engineering´ or bottom-up approach[2]; and (iii) the damage module in which the interaction between climate variations and the impacts in the economy is modelled. The existence or not of combinations of these economic sub-models plus a climate module determine the classification we use. For example, we consider a fully integrated IAM those models that include all modules above: an economic growth model, including the energy sector, a damage module and a climate module. We name Non-CGE-type models those that do not include an optimization procedure of the economy. In general, non-CGE models include a climate module and a damage module, some also include an energy module, but all assume different scenarios for the world economy given elsewhere (e.g. IPCC scenarios). This type of models can also be considered as the policy evaluation models described by Toth (2005), or the simulation models named by Stanton *et al.* (2008). Finally, we name the CGE-type of models those models that focus on the optimization of the detailed characterization of the economy, including the energy sector. These models have been used extensively for analyses of the impact of carbon taxes and other policy instruments in the economy and resulting emission reductions. In general, the CGE-type of models is characterized by the absence of a proper climate module.

We do not try to undertake an exhaustive review of the literature given the high number of models currently used in the climate change debate, but rather, we aim to select some relevant models, highlight their important features and identify how climate change damages are treated in those models (if they are). This paper is organized as follows: we start by reviewing the fully integrated IAMs in section 2. Section 3 is devoted to the non-CGE type of models while section 4 describes some CGE-type models. The models are only described in words in order to facilitate the reading, however, damage functions are described in mathematical form when available in their original papers.

2 Fully Integrated Impact Assessment Models

The models reviewed here are the following nine: DICE; ENTICE; RICE; FEEM-RICE; WITCH; MERGE; ICAM; MIND; and DEMETER.

DICE[3]

The Dynamic Integrated model of Climate and the Economy (DICE) comprises a set of climate-economy models developed at Yale University for the investigation of climate change. Its last version, DICE2007, incorporates a number of methodological developments and data to its previous versions, for example, DICE99 (Nordhaus, 1994; and Nordhaus and Boyer, 2000). Other models of the DICE family include the multi-region version, RICE (Regional Integrated model of Climate and the Economy – Nordhaus and Yang, 1996), and a version that introduces endogenous technology changes, ENTICE-BR (Popp, 2006). The DICE family of models views the economics of climate change from the perspective of the neoclassical economic growth theory, in which economic agents invest in capital, education and technology in order to increase consumption in the future. It is a global model that aggregates countries in

[2] "The 'bottom-up' (engineering) approach often starts with a detailed treatment of the energy-producing processes or technologies, and then asks the questions: given a particular level of demand for energy services (which may be defined in terms of the level of outputs of certain activities, such as travel, heating, air conditioning, lighting, or even steel making, etc.), what is the most efficient way of going about meeting these demands in terms of the energy technologies employed and the level of inputs. The top-down (economic) approach, on the other hand, starts with a detailed description of the macro (and international) economy and then derives from there the demand for energy inputs in terms of the demand for various sectors' outputs through highly aggregate production or cost functions" (Burniaux and Truong, 2002).

[3] The description of the DICE2007 model is based on Nordhaus (2007, 2008).

one single output, capital stock, technology and emissions. Global aggregates are estimated from data including all major countries[4] from twelve regions[5] using PPP exchange rates. The world is assumed to have its preferences defined by a social welfare function that ranks different paths of consumption that are constrained by both economic and geophysical relationships. This welfare function is the discounted sum of the population-weighted utility of per capita consumption, and is increasing in per-capita consumption of each generation, with diminishing marginal utility of consumption. The only commodity that represents the economy can be used for consumption and investment. Consumption includes market and non-market goods. Inter-generational relative importance is represented by the pure rate of social time preference (designated as the rate that provides the welfare weights on different generations) and the elasticity of the marginal utility of consumption. Thus, the model optimizes the flow of consumption over time; i.e. policies are chosen to maximize the social welfare function. "The criteria for optimal policy is an equalized marginal cost and marginal benefit such that the marginal cost of mitigation (the opportunity cost in terms of what societies give up for reducing GHG emissions by an additional unit) and the marginal benefit of mitigation (the climate change damage, expressed in monetary terms, avoided by an additional unit of emission reduction) are the same" (Toth, 2005).

The current version of the DICE model, DICE2007, runs on periods of 10 years; variables are in general given in flows per year although some variables are represented in flows per decade, and transition parameters are defined as flows per decade. Population growth and the labour force are also exogenous in the DICE model, and these are represented by logistic equations, in which the growth of population in the first decade is given but it declines so that population approaches a limit of 8.5 billion.

Two major decision variables in the DICE model represent the overall savings rate: the savings rate for physical capital accumulation and the emissions control for GHG. Capital accumulation is endogenously determined by optimizing the flow of consumption over time. Each region is endowed with an initial stock of capital and labour, and an exogenous region-specific level of technology. Technological changes are of two forms (apart from the ENTICE-BR model, described below): economy-wide and carbon-saving, which is modelled as reducing the ratio of CO_2 emission to output. Output is determined with a constant-return-to-scale Cobb-Douglas production function in capital, labour and energy, which takes the form of either carbon-based or non-carbon-based fuels. Carbon fuels are limited in supply and fuel substitution over time from carbon-based to non-carbon-based is possible as carbon-based fuels become more expensive due to exhaustion or policies.

DICE models introduce the natural capital of the climate system as an additional type of capital stock; i.e. GHG concentration is seen as a negative natural capital and emissions reductions as investments that lower the stock of negative natural capital. In this framework, the economic agents substitute consumption in the present for preventing climate change in the future and increasing future consumption possibilities. DICE2007 differs from previous versions of the DICE model by including a backstop technology [6] for non-carbon-based energy, which allows the complete replacement of all carbon fuels at a relatively high price that is decreasing over time.

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[4] These are seventy one countries representing 97% of emissions, 94% of the World output and 86% of the population.

[5] The US, EU, other high income countries, Russia, Eastern Europe and the non-Russian former Soviet Union, Japan, China, India, the Middle East, Sub-Saharan Africa, Latin America and other Asia.

[6] Backstop technology is defined as a technology that produces a substitute to an exhaustible resource by using relatively abundant (no scarcity) production inputs and turns the reserves of the exhaustible resource obsolete. It provides resources at a constant marginal cost for an indefinitely long time (Dasgupta P. and G. Heal, 1979), *Economic Theory and Exhaustible Resources*, Cambridge: Cambridge University Press).

The only GHG subject to controls in DICE is industrial CO_2. Other GHGs such as CO_2 emissions from land-use changes, other well-mixed GHGs and aerosols; are included as exogenous trends in radiative forcing equations. Emissions are projected as a function of (i) total output; (ii) an emission-output ratio, that varies over time, estimated for all regions and aggregated to the global level; (iii) an emission control rate determined by the climate-change policy under examination. Uncontrolled industrial CO_2 emissions are given by a level of carbon intensity times world output. Actual emissions are then reduced by the emissions-reduction rate. The DICE model assumes that incremental extraction costs are zero and that carbon fuels are optimally allocated over time by the market, producing the optimal Hotelling rents. The model imposes a limitation on total resources of carbon fuels, a similar characteristic of the MERGE model.

DICE models include a carbon cycle model; a radiative forcing equation; climate-change equations; and climate-damage relationship – that link the economy and the factors affecting climate change. The authors face the complexity of the dynamics of climate change by using a small number of equations that are empirically tractable but with a transparent theoretical basis. Accumulations of GHG is assumed to be linked to temperature rising through increases in radiative forces, this relationship being derived from empirical measures and existing climate models (e.g. MAGICC, 2007). Higher radiative forcing warms the atmospheric layer, which warms the upper ocean, and gradually warms the deeper oceans. The radiative forcing equation calculates the impact of the accumulation of GHGs on the radiation balance of the globe. The climate equations produce the mean (global) atmospheric temperature and the average temperature of the deep ocean for each time span. The model assumes that carbon flows between adjacent reservoirs: the atmosphere; a mixing reservoir in the upper oceans and the biosphere; and the deep oceans. The deep oceans provide a finite sink for carbon in the long run.

The damage function assumes that changes are proportional to the world´s output and are polynomial functions of global mean temperature change. The aggregate damage curve is derived from estimates of the damage of the twelve regions. It includes estimated damages to major sectors – agriculture, sea-level rise, health, non-market damages and catastrophic damages. Nordhaus (2007) argues that this damage function is extremely conjectural given the weak base of empirical studies on which it is based on.

$$\Omega(t) = \frac{1}{[1+\psi_1 . T_{AT}(t)+\psi_2 . T_{AT}(t)^2]} \tag{1}$$

Where:

$\Omega(t)$	Damage function (climate damages as a fraction of world output);
ψ_1, ψ_2	Parameters of the damage function;
$T_{AT}(t)$	Global mean atmospheric temperatures (°C from 1990);

Tol (1996) argues that the way that intangible losses are treated in DICE is wrong: "after a monetary value has been attached to the intangible damages, DICE treats them as market goods, which they are not. Tangible income can be used for either consumption or production, whereas intangible ´income´ is consumption. Bringing the intangibles back to where they belong, i.e. in the utility function, slightly raises the optimal GHG emission reduction. This is due to the fact that in DICE all losses are subtracted from the output, which is then divided between consumption and investment. Thus, moving the intangible losses from the production to the utility function implies enhancing the prospects for economic growth, thereby increasing the possibility and need for emission abatement" (Tol, 1996).

ENTICE-BR

Popp (2006) presents a modified version of the DICE model that introduces endogenous links between climate policy and energy innovation, while keeping the global framework of the DICE model. One significant difference of the ENTICE-BR model is that, as in the regional version of the model – RICE, fossil fuels are included as input to production. Output is produced by a combination of labour, the physical capital stock and effective energy units, which are a measure of the productive capabilities of three possible energy inputs: fossil fuels, carbon-free backstop technology and energy efficiency. Technological progress is represented by changes in total factor productivity and the cost of fossil fuels and the backstop technology are subtracted from total output.

Energy units is estimated by a constant elasticity of substitution (CES) framework to aggregate fossil fuels usage, the backstop technology fuel and knowledge pertaining to energy efficiency. The backstop technology and fossil fuels are modelled as imperfect substitutes, "allowing for ´niche markets´ for the backstop technology even when the price of the technology exceeds fossil fuel prices" (Popp, 2006). In ENTICE-BR energy needs are met by consuming energy inputs or improving knowledge pertaining to energy efficiency. Technological advances can improve energy efficiency or lower the costs of using the backstop fuel. These knowledge stocks are created by the accumulation of previous R&D, which is endogenous to the ENTICE-BR model. The level of R&D spending (and the stock of knowledge) increases when climate policies are introduced. Also, the parameters related to the R&D spending are chosen to characterize diminishing returns to energy research over time.

RICE

Nordhaus and Yang (1996) described the RICE (Regional Integrated model of Climate and the Economy) model, a regional and dynamic, general-equilibrium model of the economy that integrates economic activity with emissions and consequences of GHG and climate change. In the RICE model the world is divided in ten regions[7], each endowed with an initial capital stock, population and technology. Like in the DICE model, capital accumulation is determined by optimizing the flow of consumption over time, and output is produced by a Cobb-Douglas production function in capital, labour and technology. Population and technology are exogenous to the model, and endogenous GHG emissions are limited to CO_2. The main differences between RICE and DICE in terms of modelling regard (i) the preference function of each region is a utility function that is the sum of discounted utilities of per capita consumption times population. The global social welfare is then determined by countries´ consumption levels; and (ii) the regional output identity that in RICE considers trade among the regions. Within each region the optimal path of the control variables (capital investment and carbon energy input) is chosen to maximize welfare.

Other differences to the DICE models include: RICE assumes that in the long-run capital is fully mobile among regions, so that the real return on capital is equal across regions. In addition, RICE includes region-specific emissions equations, a global concentrations equation, a global climate change equation and regional climate change relationships. The authors argue that the goal in creating the different regions is to structure the problem so that the non-cooperative equilibrium is equivalent to the full but enormous game with approximately 200 countries. It is accomplished by allocating the smaller countries to groups so that within each group the national benefits from slowing climate change are equal.

[7] The US; Japan; China; EU; Former soviet Union; India; Brazil and Indonesia; 11 large countries; 38 medium-sized countries; and 137 small countries. In some analyses, the authors aggregate regions 6 to 10 (India to small countries) in one region (rest of the world, ROW) in order to reduce the severe computational complexity of the solution.

Thus, RICE assumes that all countries within a multi-country region are similar in terms of their sizes, mitigation cost functions and damage functions.

The RICE model presents a different philosophy from other models for estimating strategies to cope with climate change: the baseline scenario is calibrated to market equilibrium of the world economy with all the differences in population, technologies and incomes. Different strategies for global warming are then calculated conditioned on the existing distribution of capital, labour and technology. These strategies are (i) the market solution (do nothing); (ii) the cooperative solution (an efficient solution given the existing distribution of income); and (iii) the non-cooperative solution (the solution in which nations select policies to maximize national preferences alone). The cooperative solution has its theoretical basis for the algorithm based on a theorem of welfare economics that states that under certain conditions a competitive equilibrium can be found by maximizing a social welfare function of (n) agents in which the welfare weight of each of the agents is adjusted to satisfy the agents´ budget constraint. The welfare weights were taken as to reflect the actual economic outcome across regions, and these are estimated so that the excess demands in all markets are zero at the given prices and welfare weights (Nordhaus and Yang, 1996). The results of the application of a new and updated version of the RICE model (RICE2009) for the evaluation of three policy scenarios is presented in Nordhaus (2009). No major differences from the RICE model were presented, apart from the updated data used in RICE2009 and the number of regions that RICE2009 deals with (twelve).

FEEM-RICE

According to Bosetti *et al.* (2006) and Buchner *et al.* (2005), the FEEM-RICE model is an extended version of the RICE model, which incorporates endogenous technical change (in addition to induced technical change) in order to respond to climate-change policies as well as to other economic and policy incentives. The model considers both learning-by-doing (*LbD*) and learning-by-researching (*LbR*) as inputs of endogenous and induced technical change, and the effect of technical change on energy intensity of production and the carbon intensity of energy use. The factors of production are labour, physical capital and carbon energy. FEEM-RICE assumes that energy-saving and climate-friendly innovation is induced by investments in R&D, which contributes to the accumulation of the stock of knowledge (learning by researching). Learning by doing is modelled in terms of cumulated abatement efforts. Therefore, the energy technical change index (*ETCI*) is defined as a convex combination of the stocks of knowledge and abatement.

The authors model the positive externality of knowledge creation by assuming that the return of investment in R&D is four times higher than investments in physical creation. The opportunity cost of crowding out other forms of R&D is obtained by subtracting four dollars of R&D of private investment of physical capital stock for each dollar of R&D crowded out by energy R&D. The optimal path of the control variables is determined within a game-theory framework where each country (region) plays a non-cooperative Nash game in a dynamic setting that yields to an Open-Loop-Nash equilibrium. The fundamental driver of technical progress in FEEM-RICE is R&D investment, which induces knowledge accumulation and experience in emission abatement, and these variables move technology towards a more environmentally-friendly dynamic path (Bosetti *et al.*, 2006). The authors did not refer to the damage function in the papers describing FEEM-RICE, which suggests that no changes were made from the damage function used in the DICE family of models.

WITCH

The World Induced Technical Change Hybrid (WITCH) model is a top-down, Ramsey-type neoclassical optimal growth model with an energy input specification that operates as a bottom-up model. It is based on and a development of the FEEM-RICE model. It is designed to analyze optimal climate mitigation policies within a game-theoretical framework, such as FEEM-RICE, while considering endogenous technological developments in energy production and use (Bosetti *et al.*, 2007). It is considered a hard-link hybrid model since the energy sector is contained within the economy in a way that resources for energy generation are allocated optimally with respect to the whole economy. The bottom-up part of the model introduces learning-by-doing effects (experience curves) for all energy technologies while in the top-down part of the model it accounts for the accumulation of knowledge (via R&D) and its effects on energy efficiency and the cost of advanced biofuels. In addition, WITCH also has an integrated climate module that enables analysts to observe CO_2 concentrations and mean temperatures as a consequence of the use of fossil fuels. The climate module feeds a damage function that delivers the effect of climate change on the economy.

WITCH is defined for twelve macro regions of the world. In each region a social planner maximizes the welfare function. The model´s control variables – investment in different capital stocks, R&D and energy technologies; and consumption of fossil fuels – are optimized for each period of time comprising five years. A nested CES production function aggregates capital, labour and energy services to produce a single final good, and the budget constraint defines consumption as net output less investments.

Climate damage reduces gross output by the costs of the natural resources and the cost of carbon sequestration (transporting and storing the captured CO_2) for each technology. Apart from that, WITCH shares the same climate module component developed in the DICE family of models. Like in FEEM-RICE, four dollars of private investments are subtracted from final good accumulation for each dollar of R&D investment crowded out by energy R&D. The quantity of carbon captured with CCS technologies is subtracted from the carbon balance.

Energy services combine energy with stock of knowledge that represents technological advances arising from investment in energy R&D, which improves the efficiency with which energy is translated into energy services (e.g. more efficient car engines or light bulbs). Energy is a combination of electric and non-electric energy, which is obtained by adding coal, biomass and an oil-gas-biofuels aggregate. For each technology, electricity is obtained by combining three factors of production in fixed proportions: the installed power generation capacity, operation and maintenance equipments, and fuel resource consumption. The cost of electricity generation is endogenously determined in WITCH, which the authors regard as a novelty in relation to existing similar models. It is the sum of the cost of capital invested in plants and the expenditures for O&M and fuels. Since investment costs, O&M costs, fuel efficiency for each technology and fuel prices are region-specific then the authors claim that WITCH can obtain a high degree of realism in constructing relative prices of different electricity generating in the twelve regions.

In WITCH, world regions interact through five channels. First, the prices of oil, coal, gas and uranium depend on the consumption in all regions, for each period of time. Hence, investments in R&D and consumption choices in any region at any time period indirectly affect all other countries' choices[8]. Second, CO_2 emissions from each region affect the world´s average temperature, affecting the shadow

[8] The authors remark that by accounting for consumption-induced price changes they can describe rebound effects of lower fuel prices inside a region and across regions. For example, a considerable reduction in oil consumption in the US or EU stimulated by policies that promote biofuels would reduce oil prices, which in turn could stimulate the oil demand in the rest of the world and increase overall emissions.

value of carbon emissions in all regions. Third, each country´s investment decisions in electricity generation technology changes the cumulative world installed capacity, which affects investment costs via learning by doing. Fourth, the international R&D spillovers affect the costs of advanced biofuels. Fifth, if the model is used to analyze the effects of emission trading, marginal abatement costs are equalized across regions, with consequences for R&D and other investment choices. The equilibrium solution (the optimal path of investments, R&D strategies and direct consumption of natural resources) is obtained as follows: for each time period the social planner in each region takes the behaviour of other players produced in the previous time period as given, and sets the optimal value of all control variables. The process is repeated until the behaviour of each region converges, i.e. each region´s choice is the best response to all other regions´ best response to its behaviour. Bosetti *et al.* (2007) highlight that the solution to this algorithm is unique and invariant to different orderings of the regions. Damage function is the same as in DICE, but estimated per region of the world.

MERGE

Manne *et al.* (1995) describe the MERGE model, which was designed to be flexible in order to explore alternative views on a wide range of contentious issues related to climate change and policies (e.g. costs and benefits of mitigation policies, valuation and discounting issues). It consists of a series of modules representing the major processes of interest in the debate of climate change: (i) the costs of reducing GHG emissions; (ii) natural system disposition and reactions to the emissions of the gases; and (iii) the reaction of human and natural systems to changes in the atmospheric system. The three modules or sub-models in MERGE are: (i) Global 2200; (ii) the climate module; and (iii) the damage assessment module.

Global 2200 is a fully integrated applied general equilibrium model that is used to assess the costs of alternative emission constraints at the regional and global level. It divides the world into five regions[9]; each of the regions is taken as an independent price taking agent and is subject to an inter-temporal budget constraint. At each time period – MERGE uses 10-years time interval between 1990 (the base or benchmark year) and 2050, and 25-years intervals between 2050 and 2200 – supplies and demands are equilibrated through the prices of the commodities: oil, gas, coal, carbon emission rights and a numeraire good that represents a composite of all items produced outside the energy sector. The authors highlight that Global 2200 is a forward looking model rather than recursive dynamics, which is particularly important for the evolution of the prices of exhaustible resources and their eventual replacement by backstop technologies.

MERGE shares a number of similarities with the DICE family of models, both in its economic module (Global 2200) and in its damage module. For example, the welfare maximization problem involves maximizing the sum of discounted utility of consumption. However, MERGE always uses a logarithm form of the utility function[10], which implies always positive marginal utility but diminishing function of the aggregate level of consumption. It also assumes a unitary elasticity of substitution between consumption in each period of time. Each of the five regions has a single representative produce-consumer; these regions are described in highly aggregated terms: the energy sector is divided in two end-products – electric and non-electric energy – while outside the energy sector all the economy is represented in terms of dollars of real purchasing power. Aggregate economic output is allocated between

[9] The USA; other OECD nations (EU, Japan, Canada, Australia and New Zealand); Former Soviet Union; China and the rest of the world (ROW).

[10] In this sense MERGE is similar to the WITCH model.

inter industry payments for energy costs and final demand for current consumption and investment. For the economy-wide production function in each region, MERGE assumes a long-run static nested non-linear production function that depends on capital, labour, electric energy, and non-electric energy.

The rate of GDP growth is a determinant of energy demands, and depends on population and per capita productivity trends. However, because of energy-economy interactions, GDP growth rates do not uniquely determine the realized rates, with energy costs representing only one of the claims on the economy´s output. Energy consumption does not grow at the same rate as GDP: conservation possibilities are summarized through the elasticity of price-induced substitution and autonomous energy-efficiency improvements. Manne *et al.* (1995) assume population growth estimated elsewhere. The alternative sources of electricity supply considered in MERGE include: hydroelectric and other renewable; gas; oil; coal; and nuclear power plants. In addition to these existing technologies, the authors include technologies that were likely to become available by the time the model was developed: advanced combined cycle; new coal; high cost and low cost carbon-free technologies.

The climate module of MERGE focuses on three GHG: carbon dioxide, methane and nitrous oxide, and emission of these gases are divided between energy and non-energy emissions. The economic module projects energy-related emissions of each GHG by fuel type for each time period, while non-energy emissions are exogenous. The climate module estimates future GHG concentration and corresponding variation in average temperatures following (carbon-cycle) models and data found in the literature.

Climate change damages are divided in two categories: market or economic and non-market or intangible. The economic damage for period (t) and region (n), ($D_{t,n}$), equation (2), follows the assumption used in DICE that damages rise quadratically with temperature change ($d_{2,n}=2$). Non-economic damages are assumed to follow the willingness-to-pay (WTP) approach. The relationship between (*WTP*) for non-market goods and per-capita income is assumed to be S-shaped, which implies lower income regions having lower WTP, and is calibrated in order not to exceed 100% of GDP. According to equation (3), each region values ecological damages independently of where the damage occurs, which means that individuals place the same value to biodiversity losses, human health and wildlife whether these losses occur within or outside their own boundaries.

$$D_{t,n} = d_{1,n} . \Delta AT_{t,n}^{d_{2,n}} . GDP_{t,n} \quad (2)$$

$$WTP_{t,n} = \frac{d_{3,n} . \Delta AT_{t,n}^{d_{4,n}}}{\left(1 + 100 . \exp\left(-0.23 . \frac{GDP_{t,n}}{Pop_{t,n}}\right)\right)} \quad (3)$$

Where:

$D_{t,n}$ Market or economic damages for period (t) and region (n);

$WTP_{t,n}$ Non-market damages for period (t) and region (n);

ΔAT Variation on actual temperature;

ICAM

The Integrated Climate Assessment Model (ICAM, e.g. Dowlatabadi, 1998) was developed over a ten-year span at the Carnegie Mellon University, Canada. It includes five integrated modules: demographics and economics (the economy module); energy and emissions (the energy module); atmospheric composition and climate (the climate module); impacts of climate change (the damage module); and an intervention module. Its climate module represents key uncertainties about how greenhouse gases will affect climate in the form of probability distributions, elicited from experts in climatology and climate modelling. It considers the change in average global temperature due to a doubling of atmospheric CO_2 concentration, the effect on the temperature gradient from the equator to the poles and changes in precipitation by latitude.

ICAM uses 17 regions, each with its own population, economy, and policies for responding to climate change. It runs at 5-year intervals from 1975 to 2100. One of the novelties of this model is that it models the age structure of populations with 5-year ranges and the effects of an aging population on the economy. ICAM also represents uncertainties about the costs of new energy and mitigation technologies, and the rate of diffusion of technical innovation from one region to another, recognizing social resistance or acceleration of diffusion of new technologies. Another novelty of ICAM regards the introduction of “adaptive agents” that respond to goals or try to keep scenarios within acceptable ranges and avoid unlikely extreme or unacceptable results in the model. For example, one agent adjusts the carbon taxes to reach emissions reductions such as the Kyoto agreement. Regional agents can let regions opt out of global carbon taxes if the tax is unreasonably high. A global agent can set binding tighter constraints if most regions experience damage greater than 2% of GDP. It identifies and can ignore "modelling crises" where trajectories exceed plausible bounds on selected variables, such as where high shadow prices on carbon drive the price to zero.

The damage function in ICAM depends partly on the rate of change of temperatures and is separated with respect to the damage category – an estimate of the agricultural sector as a fraction of the economy and coastal zone damages due to sea level rise. ICAM presents the characteristic of allowing for damages that last longer than the period in which they were caused.

MIND

The Model of Investment and Technological Development (MIND) is an IAM of the world economy with specific focus on the energy sector, incorporating several energy-related sectors in an endogenous growth model of the world economy (Edenhofer *et al.*, 2006). MIND follows the general approach of an inter-temporal cost-effectiveness analysis: it calculates the impact of investments in different mitigation options on the overall macroeconomic costs of climate protection measured in terms of welfare losses (Edenhofer *et al.*, 2005). One interesting characteristic of MIND is that it enables a comparison of all relevant mitigation options: energy efficiency, renewable energy sources and carbon capturing and sequestration (CCS), which is rarely assessed together with the other mitigation options.

MIND is a global model, with no regional differentiation, which maximizes an aggregated social welfare function determined by per-capita consumption. The inter-temporal welfare function is optimized for the period 1995 to 2300, at an interval of five years. The model assumes inelastic labour supply given by an exogenous population scenario, which implies no trade-off between labour and leisure time, and neglects the impact of an ageing population on growth, saving rates and innovation dynamics. Its control variables are investments in the (i) economy-wide physical capital stock; (ii) renewable energy sector; (iii) fossil resource extraction sector; (iv) fossil energy sector; (v) R&D improving labour productivity; and (iv) R&D improving energy productivity. The production function is assumed as a CES between labour, capital and energy, with elasticity of substitution greater than zero and less than one, which implies all factors being essential to the production and no full substitution of factors.

The energy module in MIND reflects the importance of the energy sector in the model: it considers energy delivered from fossil fuels (coal, oil and gas); from renewable sources (wind, biomass, solar and geothermal); and non-fossil fuels (nuclear, traditional biomass and hydropower). Relevant concepts are also considered, for example, the scarcity effect (increasing marginal costs of extraction of fossil fuels); the learning-by-doing effect (increasing capital productivity as cumulative production increases), typical of bottom-up models of the energy sector; and R&D investments in energy generation. The climate module in MIND uses a simple energy-balance model to calculate the response of global mean temperature to a perturbation of the radiation balance at the atmosphere. It reproduces the short-term behaviour of MAGICC. The model focuses on the energy sector and the analysis of alternative mitigation options, not taking into account the effect of climate change damages on reducing capital and/or welfare.

DEMETER-1 / DEMETER-1CCS

DEMETER-1CCS is a growth model with learning-by-doing for fossil fuels and non-carbon energy, containing a de-carbonization option through carbon capturing and sequestration (CCS) and a climate module (Gerlagh, 2006). The model has 30 time periods of five years; one representative consumer, three representative producers (or sectors) and a public agent that can set emission taxes to reduce CO_2 emissions. DEMETER-lCCS´s production function accounts for technology that is embodied in capital installed in previous periods, and production that uses the newest vintage for which the capital stock has been installed in the directly preceding period. Energy services consist of a CES of energy produced by energy based on fossil fuel and carbon-free technologies. The model incorporates various insights from the bottom-up literature that stress the importance of learning-by-doing effects in climate change analysis (decreasing marginal production costs).

The climate module in DEMETER-1CCS follows the RICE models. The carbon cycle and climate change dynamics are included in DEMETER-1CCS by linking emissions to atmospheric, upper ocean and lower ocean CO_2 storage; and ocean and global average surface temperature. Similarly to the MIND model, there is no mention to the estimation of climate change damages in the DEMETER-1CCS model.

3 Non-CGE Models

Models of the non-CGE type are characterized by a simpler economy module than those models containing a CGE-type of economy module. They in general include a climate module and/or a bottom-up energy module but rely on economic scenarios developed elsewhere. They do not attempt to optimize the economy, i.e. estimate economic and output growth given investments in a number of sectors of the economy. In other words, some models (e.g. FUND, PAGE and E3ME) have a climate module that estimates temperature changes given an exogenous economic growth; and some (e.g. FUND and PAGE) have a damage module that estimates physical and monetary impacts of temperature changes. Other models (e.g. DNE21 and GET) are focused on the energy systems and do not include climate and damage modules. The models reviewed here are the following: FUND; PAGE; E3MG; DNE21+; and GET.

FUND

The Climate Framework for Uncertainty, Negotiation and Distribution (FUND) is a policy optimization model that advices policy maker what an optimal policy looks like, rather than evaluating the economic and climate consequences of proposed policies (Tol, 1997). FUND´s economic module is simpler than those of other IAMs. On the other hand, its damage module is more complex than the other

IAMs. The most relevant difference is that impacts of climate change in FUND depend to a large extent on the rate of climate change and on vulnerability, which is a function of per capita income.

The FUND model is specified for nine regions of the world[11] and consists of a set of exogenous scenarios and endogenous perturbations (Tol, 1999). It runs for one-year periods between 1950 and 2200, which allows for some sort of validation of results when compared with real statistics. The reason why FUND starts in 1950 is the necessity to initialize the climate-change impact module. The author claims that climate impacts are assumed to depend on the impact of the previous year, which produces incorrect climate impacts for the initial years. This would bias optimal control if the first years of simulation coincided with the first years of emission abatement. In FUND, the scenarios[12] (or growth rates) of economic and population growths are perturbed by climate change through its impact on health: population declines with climate-change related deaths, such as cardiovascular associated with heat stress[13], malaria and others. Total energy use grows with GDP and falls with the exogenous autonomous energy efficiency improvement and the policy-induced energy efficiency improvement. Similar pattern is observed between carbon dioxide emission and total energy use. The endogenous parts of FUND consist of atmospheric concentrations of CO_2, CH_4 and N_2O; the global mean temperature; the impact of CO_2 emission reduction on the economy and emissions; and the impact of climate change damages on the economy and the population.

There are two ways of reducing carbon dioxide emissions in FUND: (i) energy and carbon efficiency improvement, and (ii) forestry measures. Policies to reduce carbon emissions from energy emissions are assumed to affect technology change so that (a) the marginal cost of producing output is permanently lowered and (b) the amount of CO_2 emitted to produce one Joule of energy is also permanently lowered. Output is also lowered depending on whether the top-down or bottom-up parameterization is used[14]. Forestry measures lead to a direct uptake of CO_2 and the costs of afforestation are assumed to be quadratic in the amount of carbon sequestered. The costs of slowing deforestation are assumed to equal two-thirds of those of afforestation.

Because FUND is not a CGE-type of model, all variables used in the model are either directly or indirectly determined by exogenous scenarios. As a result, the costs associated with emission reduction policies are weighted against the avoided damage of climate change by using the criteria of comparing the net present value of average utility. Utility is assumed to be mixture of per capita income, tangible and intangible damages of climate change and air pollution, and emission reduction costs:

$$W_{j,t} = ln\left(\frac{Y_{j,t} - D_{j,t}^{Int} - L_{j,t}^{Int}}{P_{j,t}}\right) \quad \text{or}$$

$$W_{j,t} \approx ln\left(\frac{Y_{j,t}}{P_{j,t}}\right) - \Omega_{j,t} - \frac{1}{2}\Omega_{j,t}{}^{2} \tag{4}$$

[11] OECD-America (excluding Mexico); OECD-Europe; OECD-Pacific (excluding South Korea); Central and Eastern Europe and the former Soviet Union; Middle East; Latin America; South and Southeast Asia; Centrally Planned Asia and Africa.

[12] Exogenous scenarios refer to the rate of economic and population growth; autonomous energy efficiency improvements; the rate of decarbonization of the energy use; methane and nitrous oxide emissions.

[13] Heat stress only affects urban population; heat and cold stresses are assumed to affect only the non-reproductive population, which means that the number of new births at each period is not affected.

[14] FUND can run eight different optimization modes: top-down vs. bottom-up; cooperative vs. non-cooperative; with vs. without inter-regional capital transfer.

$$\Omega_{j,t} = \frac{D_{j,t}^{int} + L_{j,t}^{int}}{Y_{j,t}} \quad (5)$$

$$NPW_j = \sum_{t=1950}^{2200} W_{j,t}(1+\rho_j)^{1950-t}$$

Where:

W*j*,*t*	Welfare of region (*j*) in year (*t*);
Y	GDP;
P	total population;
L^{int}	Intangible costs of global warming;
D^{int}	Intangible costs of air pollution;
ρ	Pure rate of time preference[15].

A model of the damage estimates, dynamic in both climate and socio-economic vulnerability, is described in Tol (1996, 2002a, 2002b). The damage module has two units of measurement: people and money. Climate change damage can be due to either the rate of change (benchmarked at 0.04°C/year) or the level of change (benchmarked at 2.5°C). Damage in the rate of temperature change decreases at a speed indicated in Table 1.

Table 1: Duration of Damage memory per category [(a)]

Category	Years	Category	Years	Category	Years
Species loss	100	Tropical cyclones	5	Wetland (intangible)	50
Agriculture	10	Immigration	5	Dry land	50
Coastal protection	50	Emigration	5		
Life loss	15	Wetland (tangible)	10		

Note (a): Damage is assumed to decline geometrically such that after the displayed life-time only one per cent of the initial damage remains. Source: Tol (1997).

Damage is distinguished between market and non-market (intangible) effects. Market damages affect (i) investment, which affects economic growth, and (ii) consumption, which affects welfare. Non-market effects of climate change affect only welfare. The damage cost module in FUND is an attempt to include some of the dynamics of climate change, namely, the issues of non-benchmark climate change (the fact that societies will not confront the impacts of climate change as measured in the current socio-economic ´equilibrium´, the benchmark climate change impact) and socio-economic vulnerability (the fact that poorer regions are more vulnerable to climate change than richer ones). The author highlights that a large share of the damage module is based on informed guesses. FUND´s damage cost module was defined as follows:

$$IC_t = \frac{YpC_t}{1+YpC_t/_{20,000}} \cdot \frac{1+YpC_0/_{20,000}}{YpC_0} \quad (6)$$

$$C_t{}^S = \frac{SC}{60} . Y_t . IC_t . \frac{1}{2}\left(\frac{|\Delta T_t|}{\Delta T_0} + \left(\frac{|\Delta T_t|}{\Delta T_0}\right)^2\right) + \rho_S . C_{t-1}^S \quad (7)$$

[15] Discount rates are set to 1% per year for all regions and are fixed over time.

$$C_t{}^{A} = C_t{}^{A,L} + C_t{}^{A,R} \tag{8}$$

$$C_t{}^{A,L} = \frac{1}{6}.A.Y_t.IC_t.\frac{T_t - T_0}{T_0}$$

$$C_t{}^{A,R} = \frac{5}{6}.\frac{A}{60}Y_t.IC_t.\frac{1}{2}\left(\frac{|\Delta T_t|}{\Delta T_0} + \left(\frac{|\Delta T_t|}{\Delta T_0}\right)^2\right) + \rho_A.C_{t-1}^{A,R}$$

$$D_t{}^{H} = D_t{}^{H,L} + D_t{}^{H,R} \tag{9}$$

$$D_t{}^{H,L} = \frac{1}{6}.H.P_t.\frac{T_t - T_0}{T_0}$$

$$D_t{}^{H,R} = \frac{5}{6}.\frac{H}{60}P_t.\frac{1}{2}\left(\frac{|\Delta T_t|}{\Delta T_0} + \left(\frac{|\Delta T_t|}{\Delta T_0}\right)^2\right) + \rho_D.D_{t-1}^{H,R}$$

$$C_t{}^{Agr} = C_t{}^{Agr,L} + C_t{}^{Agr,R} \tag{10}$$

$$C_t{}^{Agr,L} = Agr^L.Y_t^{Agr}.\frac{T_t - T_0}{T_0}$$

$$C_t{}^{Agr,R} = Agr^R.Y_t{}^{Agr}.\frac{1}{2}\left(\frac{|\Delta T_t|}{\Delta T_0} + \left(\frac{|\Delta T_t|}{\Delta T_0}\right)^2\right) + \rho_{Agr}.C_{t-1}^{Agr,R}$$

$$C_t{}^{Hr} = C_t{}^{Hr,L} + C_t{}^{Hr,R} \tag{11}$$

$$C_t{}^{Hr,L} = \frac{1}{6}Hr.Y_t.\frac{HA_t - HA_0}{HA_0}$$

$$C_t{}^{Hr,R} = \rho_{Hr}.C_{t-1}^{Hr,R} + \begin{cases} \frac{5}{6}.\frac{Hr}{60}.Y_t.\frac{1}{2}\left(\frac{|\Delta HA_t|}{\Delta HA_0} + \left(\frac{|\Delta HA_t|}{\Delta HA_0}\right)^2\right), if\ \Delta HA_t > 0 \\ \frac{1}{5}.\frac{1}{6}.\frac{Hr}{60}.Y_t.\frac{1}{2}\left(\frac{|\Delta HA_t|}{\Delta HA_0} + \left(\frac{|\Delta HA_t|}{\Delta HA_0}\right)^2\right), if\ \Delta HA_t \leq 0 \end{cases}$$

Where:

IC	Factor at which intangible losses increase (relates to per-capita income);
YpC	Income per capita;
C^S	Loss of species and ecosystems (intangible);
SC	Species loss coefficient in fraction of GDP;
Y	Income;
ρ	Discount factors;
T	Temperature;
C^A	Human amenities losses (intangible);
$C^{A,L}$	Human amenities losses due to the level of climatic change;
$C^{A,R}$	Human amenities losses due to the rate of climatic change;
A	Amenities losses as a fraction of GDP;
D^H	Number of deaths related to heat stress damages (due to level (*L*) and rate (*R*) of change);

D	Death losses as a fraction of GDP;
P	Population;
C^{Agr}	Agricultural damages (due to level (*L*) and rate (*R*) of change);
Agr	Agricultural losses as a fraction of GDP;
Hr	Hurricane losses as a fraction of GDP;
HA	Hurricane activity;

The number of deaths related to cold stress, (D^C), follows the same scheme as the number of deaths related to heat stress, equation (9), but with different parameters. The costs with heat and cold stresses are described in equation (12). The number of additional deaths due to hurricane is estimated exactly as in equation (11), and the costs follow from multiplication by the first part of equation (12), the value of a statistical life:

$$C_t^{HC} = (250{,}000 + 175.YpC_t).(D_t^H + D_t^C) + \rho_L.D_{t-1}^{HC} \tag{12}$$

Other damage costs in FUND include:

$$C_t^{L} = PL_t.3YpC + \rho_L.C^L{}_{t-1} \tag{13}$$

$$PL_t = \frac{L}{60}.\frac{1+{}^{YpC_0}/_{500}}{1+{}^{YpC_t}/_{500}}.P_t.\frac{|\Delta SL_t|}{0.04}$$

$$D_{t,j}{}^{E} = 0.4.YpC_{t,j}.\textstyle\sum_i \mu_{i,j}.PL_{i,j} + \rho_E.C_{t-1}^{E}$$

$$C_t^{CP} = C_t^{CP,L} + C_t^{CP,R} \tag{14}$$

$$C_t^{CP,L} = \frac{1}{4}.CP.Y_t.\frac{SL_t - SL_0}{SL_0}$$

$$C_t^{CP,R} = \rho_{CP}.C_{t-1}^{CP,R} + \begin{cases} \frac{3}{4}.\frac{CP}{60}.Y_t.\frac{1}{2}\left(\frac{|\Delta SL_t|}{\Delta SL_0} + \left(\frac{|\Delta SL_t|}{\Delta SL_0}\right)^2\right), if\ \Delta SL_t > 0 \\ \frac{1}{5}.\frac{3}{4}.\frac{CP}{60}.Y_t.\frac{1}{2}\left(\frac{|\Delta SL_t|}{\Delta SL_0} + \left(\frac{|\Delta SL_t|}{\Delta SL_0}\right)^2\right), if\ \Delta SL_t \le 0 \end{cases}$$

$$C_t^{DL} = C_t^{DL,L} + C_t^{DL,R} \tag{15}$$

$$C_t^{DL,L} = \frac{1}{2}.DL.Y_t.\frac{SL_t - SL_0}{SL_0}$$

$$C_t^{DL,R} = \rho_{DL}.C_{t-1}^{DL,R} + \begin{cases} \frac{1}{2}.\frac{DL}{60}.Y_t.\frac{1}{2}\left(\frac{|\Delta SL_t|}{\Delta SL_0} + \left(\frac{|\Delta SL_t|}{\Delta SL_0}\right)^2\right), if\ \Delta SL_t > 0 \\ \frac{1}{5}.\frac{1}{2}.\frac{DL}{60}.Y_t.\frac{1}{2}\left(\frac{|\Delta SL_t|}{\Delta SL_0} + \left(\frac{|\Delta SL_t|}{\Delta SL_0}\right)^2\right), if\ \Delta SL_t \le 0 \end{cases}$$

$$C_t^{WL,T} = \rho_{WL,T}.C_{t-1}^{WL,T} + \begin{cases} \frac{1}{2}.\frac{WL}{60}.Y_t.\frac{1}{2}\left(\frac{|\Delta SL_t|}{\Delta SL_0} + \left(\frac{|\Delta SL_t|}{\Delta SL_0}\right)^2\right), if\ \Delta SL_t > 0 \\ \frac{1}{5}.\frac{1}{2}.\frac{WL}{60}.Y_t.\frac{1}{2}\left(\frac{|\Delta SL_t|}{\Delta SL_0} + \left(\frac{|\Delta SL_t|}{\Delta SL_0}\right)^2\right), if\ \Delta SL_t \leq 0 \end{cases}$$

$$C_t^{WL,I} = \rho_{WL,I}.C_{t-1}^{WL,I} + \begin{cases} \frac{1}{2}.\frac{WL}{60}.Y_t.IC_t.\frac{1}{2}\left(\frac{|\Delta SL_t|}{\Delta SL_0} + \left(\frac{|\Delta SL_t|}{\Delta SL_0}\right)^2\right), if\ \Delta SL_t > 0 \\ \frac{1}{5}.\frac{1}{2}.\frac{WL}{60}.Y_t.IC_t.\frac{1}{2}\left(\frac{|\Delta SL_t|}{\Delta SL_0} + \left(\frac{|\Delta SL_t|}{\Delta SL_0}\right)^2\right), if\ \Delta SL_t \leq 0 \end{cases}$$

Where:

C^L	Costs of people leaving due to hurricane end/or flooding;
PL	Number of people forced to migrate;
D^E_j	Costs of people in region (*j*);
$\mu_{i,j}$	The fraction of people leaving region (*i*) that enter region (*j*);
SL	Sea level;
C^{CP}	Costs of coastal protection;
C^{DL}	Costs of dry land loss;
$C^{WL,T}$	Tangible costs of wetland loss;
$C^{WL,I}$	Intangible costs of wetland loss;

PAGE95

Policy Analysis for the Greenhouse Effect, PAGE, is a computer simulation model developed since 1992 for use in decision making within the European Commission. It was designed to capture the essential aspects of the climate change problem in a minimal number of computations; i.e. it was designed to be simple, transparent to decision makers and fast running. For a given set of policies, the PAGE model is run repeatedly using a random sample of uncertain input parameters (from a set of parameters defined by expert opinion), building up an approximate probability distribution for each model output: temperature rise, climate change damages, adaptive and preventative costs. This enables decision makers to perform a risk analysis and select the policy that balances the costs of intervention against the benefits of mitigating potential impacts (Plambeck *et al.*, 1997).

PAGE emphasizes on the climate model, which estimates the excess concentration of each GHG caused by human activities. The economic module, which is restricted to estimating the damage cost associated with the risen temperature. The level of damage depends on the rate at which temperature rises as well as on the magnitude of increase. In this regard, PAGE95 takes an enumerative approach in which the total damage of climate change is the sum of damages in individual sectors, which PAGE considers only two: economic and non-economic. Plambeck *et al.*, (1997) recognize that this approach for estimating the damage costs of climate change leads to lower valuation of impacts than the more traditional general equilibrium approach used in other IAMs, which can account for higher order of interactions such as the impact of changes in agricultural output on the food industry. However, the authors believe that using highly aggregated damage estimates from the literature allows PAGE95 to capture interaction effects implicitly.

The PAGE95 model assumes 1990 as the base year; considers seven regions of the world[16] and two GHG (CO_2 and CH_4). The size of the periods of time for which PAGE95 estimates results increases over time, allowing for higher computational efforts to concentrate in earlier periods when emission forecasts are more accurate than in later periods[17]. Impacts are assumed to occur only for temperature rise in excess of a tolerable rate of change, ($TR_{d,r}$), or temperature changes above the tolerable plateau, ($TP_{d,r}$). The tolerable plateau in the European Union, the focus region, ($TP_{d,0}$), and the tolerable rate, ($TR_{d,0}$), are uncertain parameters; and tolerable levels and rates in other regions are assumed to be proportional to the values for the focus region, by assuming uncertain regional multipliers, (F_r). Adaptation policies can increase the tolerable level of temperature rise. The regional impact of global warming corresponds to temperature increase in excess of an adjusted tolerable level:

$$TR_{d,r} = TR_{d,0}.F_r \quad \text{and} \quad TP_{d,r} = TP_{d,0}.F_r \tag{16}$$

$$ATR_{i,d,r} = TR_{d,r} + Slope_{i,d,,r} \quad \text{and} \quad ATP_{i,d,r} = TP_{d,r} + Plat_{i,d,r} \tag{17}$$

$$ATL_{i,d,r} = min\{ATP_{i,d,r}, ATL_{i-1,d,r} + ATR_{d,r}.(Y_i - Y_{i-1})\} \tag{18}$$

$$I_{i,d,r} = max\{0, RT_{i,r} - ATL_{i,d,r}\}$$

Where:

TR	Tolerable rate of temperature change (^{0}C/year);
TP	Tolerable plateau of temperature change (^{0}C);
d	Type of damage (1=economic; 2=non-economic);
r	Regions (r=1,…,7);
i	Years (i=1,…,10);
Plat	Increase in tolerable plateau from adaptation (^{0}C);
Slope	Increase in tolerable rate of adaptation (^{0}C/year);
ATP	Adjustable tolerable plateau of an adaptive policy (^{0}C);
ATR	Adjustable tolerable rate of an adaptive policy (^{0}C/year);
ATL	Adjustable tolerable level of temperature rise (^{0}C);
Y	Analysis year;
I	Regional impact of global warming (^{0}C);
RT	Realized temperature (^{0}C);
GRW	GDP growth rate (%/year);
W	GDP loss for a 2.5^{o}C warming (%);
WF	Weights regional multipliers;
WI	Weighted impact ($M);
POW	Impact function exponent;
IMP	Reduction in impacts from adaptation (%);
CS	Cost of slope adaptation ($M/^{0}C);

[16] The European Union; the US; other OECD countries; Africa and Middle East; China and centrally planned Asia; India and Southeast Asia and Latin America.

[17] PAGE95 works with10 time periods, (*i=0,1,…10*), corresponding to years 1990, 2000, 2020, 2040, 2060, 2080, 2100, 2125, 2150, 2175 and 2200.

CP Cost of plateau adaptation ($\$M/^0C$);
CS Cost of impact adaptation ($M/%);

Climate change damages are in general estimated as a percentage of GDP lost per doubling of CO_2. PAGE95 estimates regional GDP in each period of analysis, the (exogenous) growth rate of GDP, ($GRW_{i,r}$), assumed to apply from previous analysis year up to the corresponding year of analysis, as in equation (19). Weights are used to monetize climate change impacts and allow the comparison and aggregation across the economic and non-economic sectors. These weights, ($W_{d,r}$), express the percentage of GDP lost for benchmark warming of 2.5°C in each impact sector and region (equation (20))[18].

$$GDP_{i,r} = GDP_{i-1,r}.\left(1+\frac{GRW_{i,r}}{100}\right)^{Y_i-Y_{i-1}} \tag{19}$$

$$W_{d,r} = W_{d,0}.\frac{WF_r}{100} \tag{20}$$

$$WI_{i,d,r} = \left(\frac{I_{i,d,r}}{2.5}\right)^{POW}.W_{d,r}.\left(1-\frac{IMP_{i,d,r}}{100}\right).GDP_{i,r} \tag{21}$$

PAGE95 in fact uses improved aggregate damage estimates as in Tol (1996), which correspond to a benchmark doubling of CO_2 concentration. However, PAGE95 computes damages based on temperature increase, not GHG concentration. Therefore, the damage estimates are assumed to correspond to a 2.5^0C increase in temperature. Impacts are estimated for each region, damage sector and period of analysis as a power function of regional temperature increase above the tolerable level; and an adaptive policy characterized by the factor ($IMP_{i,d,r}$) can mitigate these impacts. The damage function in PAGE95, equation (21), is calibrated to agree with a linear damage function for a benchmark temperature increase (2.5^0C) above the tolerable level, ($ATL_{i,d,r}$). It is assumed a minimum, mode and maximum values of 1, 1.3 and 3, respectively, for the uncertain parameter (*POW*).

Plambeck *et al.* (1997) clarifies that PAGE95 allows for regional and time-variable discount rate, as well as different values for discounting policy implementation and the costs related to climate change impacts. The weighted impact in a non-analysis year is assumed to equal the impact of the nearest year. Weighted impacts, equation (22), are discounted over time with time-varying discount rate for impacts, ($r_{i,r}$); aggregated over all regions and economic plus non-economic impacts to produce the net present value of climate change impacts:

$$TD = \sum_{i,d,r} AD_{i,d,r}.\prod_{k=1}^{i}\left(1+\frac{r_{i,r}}{100}\right)^{-(Y_k-Y_{k-1})} \tag{22}$$

Where:
AD Aggregate damage for every analysis period except the first and last periods;

Finally, the costs of implementing adaptive and preventative policies are estimated by assuming the EU adaptation costs to climate change produced elsewhere[19], and this information is used to estimate the uncertain adaptive cost parameters for the focus region (EU), ($CS_{d,0}$), ($CP_{d,0}$) and ($CI_{d,0}$). The corresponding adaptive costs in non-focus regions are assumed to be proportional to those of the focus

[18] The weights may be negative to represent a gain, for example, as in the case of agriculture in Northern Europe.
[19] CRU/ERL (1992), "Development of a Framework for the Evaluation of Policy Options to deal with the Greenhouse Effect: PAGE User Manual", Report for the Commission of European Communities.

region, by using a multiplicative cost factor for each region, (CF_r). The total cost of adaptation depends on the change in slope and plateau of the function representing tolerable temperature increase and on the percentage reduction in weighted impacts that occur as a result of temperature increase above the tolerable level.

PAGE2002

Hope (2006) presents the advances incorporated in the PAGE95 model for a more recent version of the PAGE model, PAGE2002. The main structural changes in PAGE2002 are the introduction of a third GHG (SF_6, Sulfur Hexafluoride), the incorporation of possible future large-scale discontinuities into the impact calculations of the model, in addition to the updated values for parameters (mostly taken from the IPCC Third Assessment Report) and the inclusion of an extra region of the world. The discontinuity issue relates to the modelling of climatic change impacts in each analysis year as a polynomial function of the regional temperature increase in that year above the time-varying tolerable level of temperature change, $(T\text{-}T_{tol})^n$.

E3ME / E3MG

The Energy-Environment-Economy Model for Europe (E3ME) is a sectoral, regionalized, econometric model of the EU. It is not a CGE, but a disaggregated time-series, cross-section econometric model. The model treats member states as distinct economic entities interacting with one another; but at the same time it is one model giving the benefits of common classifications, definitions and methodology, and with equation estimates and results capable of being aggregated to the European level (Barker *et al.*, 1999). The Energy-Environment-Economy Model of the Globe (E3MG) is a development of the E3ME model for the global economy, and includes a bottom-up energy technology model within a top-down, highly disaggregated, macroeconomic model (Barker *et al.*, 2006). The econometric equations in E3MG are reduced to two sets: energy and export demand. The energy technologies are also reduced to those for the electricity sector and those for road vehicles. Except for investment by the electricity and vehicles industries, other behavioural equations are treated as being in fixed proportions to their main determinants. Other simplifying assumptions of E3MG include: (i) that a long-run solution exists; (ii) population growth and migration are exogenous at baseline levels and sufficient labour is available from productivity growth or structural change to meet the demand for products; (iii) independent central banks are assumed to hold the rate of consumer price inflation constant.

The climate model in E3MG consists of a set of linked reduced-form models emulating the behaviour of a global circulation model. Cumulative CO_2 emissions to 2100 are derived from the MAGICC model, and E3ME calculates the annual mean global temperature surface air temperature and sea-level implications of emission scenarios for GHG and sulphur dioxide. There is no mention to the consideration of climate change damage in E3MG.

DNE21+

Sano *et al.* (2006) describe the DNE21+, a world energy systems model that minimizes the total cost of energy systems necessary to meet exogenous final energy demands for a hundred years. It considers the technological change endogenously for three technologies (wind power, photovoltaics and fuel-cell vehicles). R&D investment costs in technology are treated exogenously in DNE21+. The model represents the energy supply sectors in the bottom-up fashion and the end-use energy sectors in the top-down fashion. It models eight types of primary energy sources: gas, oil coal, biomass, hydro and geothermal, PV, wind and nuclear power. The end-use energy sector of the model is disaggregated into four types of secondary energy: solid fuel, liquid fuel, gaseous fuel and electricity. Liquid fuels are decomposed into gasoline, light fuel oil and heavy fuel oil. Electricity demand is expressed by load duration curves of four types of time periods: instantaneous peak, peak, intermediate and off-peak periods. Energy savings in end-use sectors are modelled using the long-term price elasticity of electricity and non-electricity.

DNE21+ disaggregates the whole world into 77 regions, one region being a country or a region of a large country such as the US, China and Russia. It considers a time range that covers the 21st century: in five-year intervals from 2000 to 2030; ten-year interval until 2050; and 25-year interval until 2100. The world regions are linked by inter-regional trading of eight items: coal, crude oil, synthetic oil, methane, methanol, hydrogen, electricity and CO_2. The transportation mode is selected endogenously using the criteria of the least cost. A number of assumptions regarding primary energy potentials, costs and technologies are necessary; and these are obtained in databases and studies in the literature. Future scenarios of population, GDP growth and final energy demands are derived from IPCC SRES (B2).

In summary, the DNE21+ model focuses on the energy module, which is very detailed and rich in terms of energy sources and technologies. However, it does not include a climate module, which does not allow analysts to investigate the impact of changes in GHG emissions in average temperatures. Neither a damage module is cited in the reference used to describe this model.

GET / GET-LFL

The Global Energy Transition-Limited Foresight with Learning (GET-LFL) is an energy system model, such as DNE21+, that combines learning-by-doing and an optimization approach based on limited foresight (Hedenus *et al.*, 2006). GET, an earlier version of GET-LFL (Azar *et al.*, 2005) is a globally aggregated model that has three end-use sectors: electricity, transportation and heat – low and high temperature for the residential, service, agricultural and industrial sectors. Primary energy supply sources include coal, oil, gas, nuclear power, hydropower, biomass, wind and solar energy, which can be converted into heat, electricity and hydrogen. The transportation sector is divided into aviation, ships, trains, cars and trucks, and considers explicitly the costs for vehicles and fuel infrastructure. Carbon capture and storage is an abatement technology in the model that can be used on fossil fuels and biomass, but nuclear power is constrained to the present electricity production due to the political controversy surrounding this technology (Hedenus *et al.*, 2006).

Learning-by-doing is introduced in GET-LFL via both the cost of energy capital and vehicles, and the efficiency of conversion technologies. The energy capital costs are reduced by the learning rate for every doubling of cumulative installed capacity. Learning is assumed to partially diffuse between different technologies, at a spillover factor set equal to 0.5[20]. The model is based on iterative optimization with limited foresight, which means that for each time period the model maximizes the sum of consumer and producer surpluses for the following thirty years. The costs for the different technologies are assumed constant and equal to the cost level in the beginning of the period. In the next time period a new optimization is made with the decision variables from the initial period as inputs. In this period the costs of different technologies can vary because of learning-by-doing in previous periods. In summary, GET-LFL aims to simulate the energy market with complete spillover of know-how between companies and with an emission target set by policy makers. However, the authors acknowledge that the model´s results

[20] A spillover factor equal to 0.5 means that investing 1kW in say coal gasification leads to the same drop in the cost of biomass gasification (per kW) as investing 0.5 kW in biomass gasification (Hedenus *et al.*, 2006).

are heavily dependent on the assumptions that were made. Again, as an energy system model, GET-LFL does not include a climate module and has no treatment of climate change damages.

4 CGE-Type Models (Economy and Energy Modules)

In general, CGE models have a detailed set of equations defining several sectors of the economy by means of aggregated production functions and consumers´ utility functions. The list of CGE models available in the literature is vast. Some of these models were adapted or extended, by means of the introduction of a detailed energy module, to support analyses in the climate change debate. We present only the general characteristics of some of these models and refer the reader to the literature for further details. The models reviewed here are: GTAP-E; ICES; GREEN; IMACLIM-R; AIM; and MIT-EPPA.

GTAP-E

GTAP-E is an applied CGE model, developed within the Global Trade Analysis Project (GTAP), which incorporates energy and technology issues into the original GTAP database and model (Wang and Nijkamp (2007). In other words, GTAP-E introduces an explicit capital-energy composite into the production structure of the GTAP model, which is described in Hertel and Tsigas (1997) while GTAP-E is detailed in Kremers *et al.*, (2002).

GTAP-E consists of 37 industries of 20 countries in 10 regions. Each industry is associated with the production of one single traded commodity, which can be seen as domestically produced or imported with respect to each region. Each region is represented by a regional household[21], a private household and the producers that produce the domestic variant of each commodity. The regions´ welfare, given by a Cobb-Douglas function that ensures that private and government expenditures and savings represent a constant share of the regions´ income, is then maximized given a regional budget constraint. The production function is assumed to have constant returns to scale in a nested structure. In the first level, output is produced using a composite of value added and energy plus other inputs; in the second level, value added and energy is produced using natural resources, land, labour and the capital-energy composite, which are assumed as endowment. In a third level, energy is produced using electric and non-electric inputs.

ICES

The Inter-temporal Computable Equilibrium System (ICES) is a recursive dynamic general equilibrium model based on the GTAP database and developed as an extension of the GTAP-E model. The model is disaggregated in 8 regions of the world and 17 production sectors; the time frame ranges between 1997 (base year) and 2050. Like in GTAP-E, the production functions are represented by CES functions, but peculiar to ICES is the isolation of energy factors that are taken out from the set of intermediate inputs and are inserted as primary production factors in a nested level of substitution with capital[22]. The model accounts for the main GHG emissions: carbon dioxide, methane and nitrous oxide.

Two industries are treated in ICES differently from other industries in a sense that they are not related to any region: international transport and international investment production. The former relates to the production of transportation services associated with trade between regions and is produced by

[21] This is a hypothetical agent that collects all the income in the region, which is spent on private expenditure (by the private household), on government expenditures and on savings.
[22] ICES overview of the model, available online at http://www.feem-web.it/ices/

means of factors submitted by all regions. Similarly, a hypothetical world bank collects savings from all regions and allocates investments throughout the regions. ICES´s dynamics are driven by two sources. The first is endogenous – the capital and foreign debt evolution processes driven by endogenous investment decisions; and the evolution of natural resources. The second is exogenous – assumptions regarding the evolution of parameters and exogenous variables that are imposed to the model in order to reflect their evolution.

GREEN[23]

Nicoletti and Oliveira-Martins (1992) used GREEN, a global dynamic applied general equilibrium model, to study the economic effects of policies aiming to reduce carbon dioxide emission in Europe. Particularly, they were concerned with the implications of the European Commission (EC) proposal to impose a mixed energy/carbon tax for the world distribution of emissions and the competitiveness of the EC economy. GREEN incorporates full bilateral trade linkages between twelve regions of the world[24], and allows for a large and flexible regional disaggregation, while at the same time preserving sufficient sectoral detail. These characteristics make GREEN particularly well suited for the simulation of different kinds of regional and global agreements to reduce carbon emissions.

GREEN focuses on the relationships between depletion of fossil fuels (oil, natural gas, and coal), energy production and use, and CO_2 emissions; i.e., the energy sector and its linkage to the economy. Each fuel source, as well as the non-fossil energy – electricity – can be replaced in the future by "backstop" technologies, which are assumed to become available at an identical time period in all regions. Fuel prices are exogenous and identically given across all regions. For each fossil fuel there are two alternative backstop technologies: one carbon-free and one carbon-based. For electricity, the backstop technology is carbon-free (e.g. nuclear fusion, solar or wind power). There are eight energy-producing sectors in GREEN: Coal mining, Crude oil, Natural gas, Refined oil, Electricity-gas-water distribution, Carbon-based back-stop, Carbon-free backstop, Carbon-free electric back-stop. The three non-energy producing sectors are Agriculture, Energy-intensive industries, and Other industries and services. There are four consumption goods: Food beverages and tobacco, Fuel and power, Transport and communication, and Other goods and services. There are five different types of primary factors: labour, sector-specific "old" capital, "new" capital, sector-specific fixed factors (for each fossil fuel type, and for the carbon free backstop), and land in agriculture.

Imaclim-R

Imaclim-R is a multi-sector, multi-region[25] recursive growth model projecting the world economy up to 2100 on a year basis (Crassous *et al.*, 2006). The model uses a recursive dynamic framework where economic pathways are represented through a sequence of static general equilibria linked by dynamic equations. These successive (Walrasian) equilibria are computed under the constraints imposed by the availability of production factors and inter-sectoral technical relations at each time period. The outcome is a set of values for output levels, price structure and investment sent to dynamic equations which represent population dynamics, fossil fuel resource depletion and technical change. Technical change encompasses

[23] Review based on Burniaux and Truong (2002).
[24] The US, Japan, EC, Other OECD, Central and Eastern Europe, The former Soviet Union, Energy-exporting LDCs, China, India, Dynamic Asian Economies (Hong Kong, Philippines, Singapore, South Korea, Taiwan and Thailand), Brazil and Rest of the World (RoW).
[25] Sectors are 10: coal, crude oil, natural gas, oil products, electricity, construction, composite good, air transport, sea transport, terrestrial transport. The regions are 5: OECD90, Ref, Asia, ALM and the OPEC region.

labour productivity and technical coefficients and results in a new production frontier used to compute the subsequent equilibrium. In an autonomous technical change framework, the new parameters of this new production frontier come from exogenous trends, whereas under endogenous technical change assumptions, they come systematically from endogenous relations between cumulated investments and technical progress (Crassous *et al.*, 2006).

The model is calibrated for year 1997 using data from the GTAP database, IEA/OECD physical database for energy and transportation data from the World Road Statistics Database. Producers are constrained by fixed capacities (the depreciated sum of previous quantities of resources) and the technical characteristics of the equipment stock that result from past decisions. Consumers´ final demand is derived by solving the utility maximization problem subject to income and time constraints. Investment allocation across regions and sectors is governed by the expectations of future profits. Finally, the equilibrium clears international markets for goods and capital.

AIM

AIM/Dynamic Global is a multi-region (Japan, the USA, Other OECD countries, Former Soviet Union, China and Rest of the World) multi-sector global dynamic optimization model (Masui *et al.*, 2006). It maximizes global utility derived from discounted utility from the final consumption over the entire time period (1995-2100). Global utility is the (Negishi) weighted sum of regional utilities. The model is solved in 5-year intervals from 1995 to 2000 and 10-year intervals from 2000 onwards. Capital, labour, energy and non-energy intermediate goods are the inputs for production of each sector´s representative commodity. AIM considers energy-saving investments in the manufacturing sector alone, and simulates up to 2030 technologies that are currently in use. Beyond 2030, it assumes the interplay between investment, energy efficiency and emissions reductions remains constant at 2030 levels; and that least expected technology innovation occurs until 2100. Carbon dioxide emissions from fossil fuels combustion are taken as endogenous, while other emission sources (e.g. land use and industrial processes) are exogenous. The distribution of CO_2 emissions among regions is calculated endogenously based on the criterion of equal marginal reduction cost (Masui *et al.*, 2006).

MIT EPPA

The Emissions Prediction and Policy Analysis (EPPA) model is a recursive-dynamic multi-regional (16 regions) general equilibrium model of the world economy that is built on the GTAP dataset and additional data for urban gas emissions and GHG gases: CO_2, CH_4, N_2O, HFCs, PFCs and SF_6 (Yang *et al.*, 2005). The base year for EPPA is 1997, but from 2000 onwards it is solved recursively at 5-year intervals. All production sectors and final consumption are modelled using nested CES production functions, in some cases Cobb-Douglas and Leontief forms. The model incorporates a social account matrix (SAM) that includes the inter-industry flow (input-output tables) of intermediate goods and services among industries, delivery of goods and services to final consumption, and the use of factors in production. It has been adapted to incorporate health effects of air pollution (EPPA-HE) via the introduction in the SAM of a household production sector that provides ´pollution health service´ to final consumption to capture economic effects from mortality and morbidity from acute exposure to air pollutants.

5. Discussion

This working paper aimed to review the main characteristics of the models frequently used to support decision-making in the climate change arena. Table 2 summarizes some of their characteristics. In addition, it aimed to focus the review on the treatment of the climate change damage in these models. Table 3 summarizes some characteristics of the damage functions in the models reviewed here.

Similar studies are available in the literature. For example, Tol and Frankhauser (1998) reviewed twenty IAMs in an attempt to summarize how these models represent climate change impacts. The authors observed that the monetization of damages was based on a small number of studies[26], mostly developed to the USA, a trend still in practice. In addition, these authors concluded that the most important improvement the reviewed IAMs should undertake regarded the dynamic representation of climate change damage, with credible functional forms expressing damage as a function of changing socioeconomic circumstances, vulnerability, degree of adaptation, and the speed and level of climate change. Another example of a review of damage functions in different IAMs includes Stanton *et al.* (2008). These authors highlighted three concerns regarding damage functions found in IAMs: (i) the degree of arbitrariness in the choice of parameters; (ii) the functional form used in damage functions, which can limit models´ ability to portray discontinuities (the threshold temperature at which damages are potentially catastrophic); and (iii) the fact that damages are represented in terms of losses of income, not capital[27].

Most IAMs derive damage functions based on damage estimates related to doubling the CO_2 concentration from the pre-industrial level accounts. For example, these damages accounted for 1% of global GDP (Nordhaus, 1991); 1.3% (Cline, 1992); 1% to 1.5% (Frankhauser, 1993, 1994); 1.4% (Manne *et al.*, 1995); and 1.9% (Tol, 1996). However, many valuable goods and services are not included in conventional national income, which suggests that damage functions based on a fraction of GDP may underestimate the damage costs of climate change. For example, non-market or intangible damages of climate change, such as human health effects and losses of ecosystems or species.

As also observed by Tol and Frankhauser (1998), most IAMs represent climate damages in a reduced or simple form, one or two equations associating aggregate damages to a climate variable, in general average global surface air temperature. Models that use two damage equations in general separate market and non-market damages, an approach that allows such damages to feed back differently into other parts of the IAM. However, several issues arise when intangible costs are included in the total damage of climate change. For example, (i) biodiversity losses are difficult to allocate among countries; (ii) given that intangible losses are based on the WTP approach then poorer countries tend to place lower costs on ecological damages than rich countries; (iii) the assumption that poorer countries will suffer more than richer countries with climate change may not be true as developing countries may have higher market damages since their economies tend to be more dependent on climate-sensitive sectors (e.g. agriculture), but if non-market damage costs are higher than market damages costs then developed countries may suffer more than poorer countries. Thus, the way the non-market or intangible damages are estimated play an important role on total damage costs estimates.

[26] The reader can refer to Demeritt and Rothman (1999) and Tol (2008) for an assessment of these studies.

[27] Damages subtracted from output are costs that reduce consumption once, with no effects on capital, production or consumption in the following periods of time (exception is the FUND model). Some categories of the climate change damage should reduce capital, other than income (e.g. coastal properties and human settlement damages) (Stanton *et al.*, 2008).

Table 2: General characteristics of IAMs and other models

Model	*Regional or global*	*GHG gases*	*Number of economic sectors*	*Time span*
Fully Integrated IAM				
DICE2007	Global	CO_2	1 single product (sector)	10-year periods up to 2200
FEEM-RICE	Regional: 10 regions	CO_2	1 single product (sector)	10-year periods up to 2200
WITCH	Regional: 12 regions	CO_2	1 single product (sector)	5-year periods; for 100 years
MERGE	Regional: 5 regions	CO_2, CH_4, N_2O	Energy products (electric and non-electric)	10 years from 1990 to 2050; 25 years from 2050 to 2200.
ICAM	Regional: 17 regions	CO_2	Energy types: oil, gas coal and non-fossil	5-year periods; from 1975 to2100
MIND	Global	CO_2 and SO_2	Aggregate production; fossil energy generation; fossil fuel extraction; renewable energy; R&D	5-year periods; from 1995 to 2300
DEMETER	Global	CO_2	3 sectors: final consumption good; energy based on fossil fuels, and energy based on carbon-free technologies	5-year periods; for 150 years
Non-CGE models				
FUND	Regional: 9 regions	Industrial CO_2	----	1-year periods; from 1950 to 2200
PAGE2002	Regional: 8 regions	CO_2, CH_4, SF_6	----	10-year (1990-2000); 20-year (2020-2100) and 25-year (2125-2200)
E3MG	Global	CO_2	Energy and export demand	10-year periods; 2000 to 2100
DNE21+	Regional: 77 regions	CO_2	Energy sector	5-year (2000-2030); 10-year (2030-2050) and 25-year (2050-2100)
GET-LFL	Global	CO_2	3 end-use energy sectors: electricity, transportation and heat	30 years
CGE models				
GTAP-E	Regional: 10 regions	CO_2	37	NA
ICES	Regional: 8 regions	CO_2	17	1997-2050
GREEN	Regional: 12 regions	CO_2	11	NA
Imaclim-R	Regional: 5 regions	CO_2	10	1-year period; from 1997 to 2100
AIM	Regional: 6 regions	CO_2	9	5-year period from 1995 to 2000; 10-year periods from 2000 to 2100
EPPA	Regional: 16 regions	CO_2, CH_4, N_2O, HFC, PFC, SF_6	----	5-year period; from 2000 onwards

Table 3: Characteristics of the damage functions in some IAMs

Model	Damage function	Sectors
	Fully Integrated IAM	
DICE2007/ ENTICE/ RICE	A fraction of world´s output; polynomial function of global mean temperature change	Agriculture, health, sea-level rise (flooding), non-market damages and catastrophic damages
FEEM-RICE	A fraction of world´s output; polynomial function of global mean temperature change	Agriculture, health, sea-level rise (flooding), non-market damages and catastrophic damages
WITCH	A fraction of world´s output; polynomial function of global mean temperature change	Agriculture, health, sea-level rise (flooding), non-market damages and catastrophic damages
MERGE	Market and non-market (WTP), both as a fraction of GDP	Follows DICE
ICAM	Depends on the rate of temperature changes	Agricultural sector as a fraction of the economy and coastal zone damages due to sea level rise
MIND	No damage treatment	----
DEMETER	No damage treatment	----
	Non-CGE models	
FUND	Specific model; includes intangible impacts;	Loss of species and ecosystems; human amenities; deaths (heat and cold) stresses; agricultural damage; hurricane damage; forced migration; coastal protection; dryland loss; tangible and intangible costs of wetlands
PAGE2002	Sum of economic and non-economic (intangible) impacts; depends on the rate and magnitude of temperature increase; polynomial function of temp	Economic and non-economic sectors; follows the FUND model
E3MG	No damage treatment	----
DNE21+	No damage treatment	----
GET-LFL	No damage treatment	----

The usual practice to derive damage functions of the reduced or simple form mentioned above is to fit a function using the few damage estimates calculated for temperature changes below 3^{o}C, equivalent to doubling CO_2 concentration from pre-industrial levels. The most usual form is given by D(t) = a. $\Delta T(t)^b$, where the parameter ´b´ determines the shape of the curve and how fast damages increase with temperature changes. Many models assert this parameter with little or no explanation or justification (Stanton *et al.*, 2008), the most common value assumed being 2 (a quadratic function of temperature change). However, "... there was never any more compelling rationale for this particular loss function then the comfort that economists feel from having worked with it before...the quadratic-polynomial specification is used…for no better reason than casual familiarity with this particular form…it has been used primarily for analytical simplicity" (Weitzman, 2009).

In summary, a common characteristic of the treatment of climate change damages within the existing models seems to be the significant degree of subjectivity involved in the choice of parameters and functional form. This inevitably leads to subjectivity in the estimated climate change damages in case of temperature changes above the current predicted (low) levels ranging between 1 and 4°C. In part this subjective judgement of researchers is necessary due to the small number of studies dedicated to estimate climate change damages (they account for 12 studies only, according to Tol, 2008). It forces researchers to extrapolate, from a small set of figures, climate change damages for higher temperature changes and for regions of the world other than those where the original studies were undertaken. As a consequence, uncertainty surrounding damage functions is inevitably high, and will only be reduced when new and updated climate change damage estimates are produced in different regions of the planet and perhaps simulating extreme climatic conditions. Such researches are costly and may take a long time to produce relevant results. Meanwhile, IAM modellers might continue to introduce their subjective judgement while deriving damage functions, and perhaps directly address the uncertainties surrounding these functions within their models (e.g. via stochastic models and/or Monte Carlo methods).

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