



Australian Government
Australian Bureau of Agricultural
and Resource Economics

ABARE CONFERENCE PAPER 05.7

The Global Economy, Trade, Environment and the Climate System (GETEC) Model and a Reference Case for Climate Policy Analysis

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8th Annual Conference on Global Economic Analysis
Radisson SAS Senator Hotel, Lübeck, Germany, 9–11 June 2005

This paper describes the new features added to the forward-looking version of the Global Trade and Environment Model (GTEMLR) to arrive at a preliminary version of an integrated assessment model of climate change – the Global Economy, Trade, Environment and Climate (GETEC) model. New additions include a climate module, a damage function, cleaner power generation technologies and new aggregation rules for all energy users to stylize the adoption and evolution of carbon-free energy technology in the economic module. GETEC is then simulated under much debated international real income convergence assumption to generate the A1 scenario of the IPCC's SRES with and without the damage function turned on. These simulations provide alternative reference cases against which a possible climate policy of emissions restriction could be compared. The results show that in general with the damage function turned on the real per person income level is lower everywhere and income convergence attained by poorer regions is also lower than without the damage function. This implies that economic costs of climate policies are likely to be lower in integrated models compared with the ones that do not have the feedbacks.

ABARE project 110042
ISSN 1447 3666

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1 *Introduction*¹

Climate change is now one of the most widely studied and debated topics. One of the reasons for that is the scope of possible consequences of the climate change and another is that we, human beings, are responsible for this. Many scientists now believe that human induced emissions of greenhouse gases (GHGs) are causing the global climate to change – average surface air temperatures will increase, sea levels will rise, rainfall pattern will change and their variability will also increase. These climatic changes may cause losses of human lives, property and other natural environments. To avoid possible damages, therefore, a foregone conclusion is that reduction in GHG emissions is a necessity.

Understanding and responding to the climate change problem poses several challenges, not least of which includes various uncertainties. First there are significant uncertainties surrounding the scientific understanding of climate change. Second, projections of human induced emissions are also uncertain. This is not to say that there is uncertainty regarding whether or not increased concentrations of GHGs will bring about climatic change – this is regarded as a given – rather that there are differences in opinions regarding the magnitude, timing and various spatial effects that will arise from a given future emissions trajectory.

Leaving the resolution of various uncertainties of scientific models to climate scientists, we, who work on social sciences and policy areas, can take what in general has been agreed by climate scientists as given and work toward a rational response to the climate change problem conditional upon the current scientific knowledge. However, as it is impossible to predict correctly the future path the global economy will take, a reasonable approach is required to deal with the resultant uncertainty of the trajectory of human induced emissions. Commonly used approaches are scenario-based. Scenarios could be designed based on some sort of convergence hypothesis as in Nakićenović et al. (2000) and/or possible grids of projected country-specific determinants of technological progress and economic growth.

Whichever approach is taken to project economic and emissions growth, if the framework does not account for any feedback between the climate system and the economy while making its projections it is likely that such a framework will incorrectly forecasting future income/productivity levels and/or the level of overall emissions. In general, as the climate-economy feedback is likely to result in losses to most economies (particularly under projections of a carbon intensive global economy) it would be expected that frameworks without these feedbacks are likely to overstate the likely level of climatic change that will occur in the absence of climate policies. Similarly, frameworks that do not account for climate-economy feedbacks would also be likely to overstate the cost of a given climate change response policy as they ignore the damage costs that may arise in the absence of such policies.

¹ We wish to thank Don Gunasekera, Helal Ahammad, Benjamin Buetre and Guy Jakeman for constructive comments, without implicating them for any remaining errors.

A rational response to climate change problem therefore requires a better understanding of the interdependence between the climate system and the economic system. In particular, given the responses of the climate system to increased concentration of greenhouse gasses in the atmosphere, we need to know the consequences of the projected climate change. This is a big question and we, as a profession, are not yet ready to be able to provide a definite quantitative answer to this all-encompassing question.

We can, however, rephrase the question in terms of measurable economic impacts and market responses to these impacts of climate changes. If projected climate change is damaging the economic system then it would also imply lower rates of economic growth and lower level of global emissions as factors of productions would be lost or damaged and economic activities would be scaled down. Hence, we can ask: what are the economic impacts of projected climate change that results from a stream of emissions of GHGs? What are the emission and the climatic consequences of the economic damages in turn? Answering both questions simultaneously is not an easy task. This means basically assessing the full consequences of current actions including the effects of climate change and possibly affecting individual choices accordingly. It needs an analytical framework that integrates economic systems and climate system together with full feedback. Clearly, a consistent answer, even speculative, derived from the integrated framework to these rephrased questions provides a reference case without active climate policy against which the outcomes of climate change response policies can be compared. This will provide a basis to perform meaningful cost-benefit analysis of alternative climate change response policies and thus help find the optimal course of human actions.

In this paper we describe a preliminary version of an integrated assessment model being developed at ABARE. It is derived by including a simplified climate module and a stylised damage assessment module, to the intertemporal version of the Global Trade and Environment Model (GTEMLR) – ABARE's general equilibrium model of the global economy. We call this integrated assessment model the Global Economy, Trade, Environment and Climate (GETEC) model.

The climate module of GETEC is similar to the one used by IPCC in its SAR (Houghton 1997). It can project changes in the global average surface temperature in response to changes in global anthropogenic emissions of greenhouse gases. The damage module employs a hockey-stick function, which differentiates regions with respective to their vulnerabilities to climate changes, to stylize the economic damages that might be inflicted upon the economic system by global temperature changes. Economic damages are represented by factor and sector neutral productivity losses, which could be viewed as losses in factor supplies at constant productivity levels or simply factors being less productive at higher temperatures or a combination of both. In addition to this the power generation sector has been re-modelled and energy aggregation functions of all energy users are re-specified to stylize the adoption and evolution of carbon-free energy technology in the economic module.

The model is then simulated under alternative scenarios to investigate whether inclusion of climatic feedback via damage assessment modeling improves the quality of climate change policy assessment. In particular, using this stylised model we investigate whether the path of real income, emissions, temperature changes, etc. are significantly different in models containing damage functions from models that do not take the economic feedbacks from climatic changes.

The remainder of the paper is divided into six sections. In section two, we describe components of GETEC and in section three we describe the climate module. The damage function is described in section four. Section five describes our approach in comparing real incomes across nations and modeling of income convergence, and section six reports the results of simulating GETEC under real income convergence similar to that of SRES A1 scenario with and without the damage function. In section seven we conclude the paper.

2 *The conceptual structure of GETEC*

As a prototype version of an integrated assessment model, GETEC consists of a combination of a dynamic model of the economic system with an environmental accounting system, called GTEMLR, a simple climate model and a damage assessment module. Each of these modules are described in the following subsections.

2.1 *An overview of GTEMLR*

GTEMLR is the intertemporal version of The Global Trade and Environment Model (GTEM), which is a multisectoral and multiregional dynamic model of the global economy developed at ABARE (Pant, 2002). The recursive version of GTEM was originally derived from the first version of GTAP model (Hertel 1997) and so at its core GTEM looks very much like the GTAP model; many of the coefficient and variable names and data headers are the same and it is solved using the same software, GEMPACK (Harrison and Pearson 2000)². GTEM, however, added the following features to the original GTAP model: a technology-bundle approach to model energy-intensive industries; a population module that generates endogenous changes in population and labor supply; a greenhouse module that tracks emissions from the production of various commodities and from the use of fossil fuels; and accumulation relationships for capital stock, debt and population that made GTEM dynamic.

The intertemporal version of GTEM (Pant, Tulpulé and Fisher, 2002), which is called GTEMLR, allows GTEM agents to be forward-looking. Because of this particular feature, GTEMLR is well suited to study problems with long time horizons, such as climate change.

² We solve GETEC using GEMPACK on a fully 64-bit environment and hence memory problem for reasonable simulation problems and aggregations are now a thing of the past. We thank Ken Pearson and Jill Harrison for making GEMPACK 64-bit compliant on PCs.

Briefly, the main features of the model can be described as follows. It contains five basic types of agents: a representative consumer, regional production sectors, importers, an international transportation sector, and a global financial centre. All agents behave competitively and take prices as given. Supply of natural resources, land, government policies, technology and tastes are exogenous. All factors in each region are owned by the regional household, which receives all factor incomes, all tax revenues and makes and receives transfer payments to and from the rest of the world. A representative consumer decides on the allocation of income of the regional household.

The current gross national income of each region is allocated to savings (units of global bonds) and to the consumption of commodities produced everywhere to maximise the utility of the representative consumer. This is done in three stages: first, a Cobb-Douglas utility function, defined over the private consumption of goods, government consumption of goods and real savings is maximised. This implies that a fixed share of gross national income is allocated to each of the three categories. The budget allocated to private and government consumption is further allocated to individual commodity composites maximizing a Cobb-Douglas utility function for government consumption and a CDE function for private consumption. In the third stage, using the Armington assumption of imperfect substitution between sources of a commodity and assuming rationality both government and private demand of each composite commodity is met from domestic and foreign sources so that the cost of each commodity composite is minimized.

Production sectors use a CES composite of the four types of factors of production, capital, labor, land and the natural resource, and combine it with other energy and non-energy material inputs to produce their output. Production technologies contain nests that allow intra-energy commodity, intra-factor and energy-factor substitution in response to relative price changes and are characterised by constant returns to scale. Each sector minimises cost by choosing inputs optimally; and industry output levels are chosen to maximise profit, given prices. There are two production sectors in GTEM—electricity and iron and steel – whose production functions are different from others. Instead of a single nested production function, each of these sectors has a technology bundle. Electricity is produced by six technologies – coal fired, oil fired, gas fired, hydro, nuclear and renewables; and iron and steel is produced by two different technologies – blast furnace and electric arc. Each technology employs a different Leontief production function. The technology-bundle industries buy CES aggregates of the outputs of corresponding technologies as inputs into their production, which is then sold to the end users. The allocation of output to different technologies is chosen to minimise the average cost of input to the respective technology-bundle industry.

Unlike technologies of the iron and steel sector, which can be considered to produce outputs that are imperfect substitutes, technologies in the electricity sector produce near homogenous output. The CES aggregation of the technologies, which treat them as imperfect substitutes, is indeed an imperfect representation of the capacity constraints faced by each technology in the short run, lumpiness of investment, and different needs of buyers, such as remote location, etc. that support the existence of niche technologies.

Competitive conditions imply price-taking behavior on the part of all agents and satisfaction of zero profit conditions in equilibrium when all markets clear. Input demands for commodities are met from domestic as well as from foreign sources. The Armington assumption of imperfect substitution between sources and the process of cost minimisation again determine the allocation of input demand between sources of supplies.

Aggregation of input and final demand for each commodity identified by source determine a region's imports by commodity and by region. This aggregation also yields a region's export of a commodity by destination and thus bilateral trade. Shipping of commodities from a source to its destination region is done by an international transport sector, which has a Leontief production technology. This sector buys inputs of transports (margin commodities) from various regions minimising the unit cost of the transport aggregate. Importers buy the transport services and the cost of transport creates the wedge between the *fob* and *cif* prices of commodities. Both the transport sector and importers satisfy zero profit conditions in equilibrium because of competition.

The savings of the regional households are pooled by the global financial center and then lent to investors residing in all regions. The allocation responds to the differential of the expected rate of return with the global rate of return that clears the market. The market clearing rate is used to service the debt or pay the savers, which guarantees that the global financial center satisfies its zero-profit condition. Regions may differ in their risk characteristics and policy regimes, therefore it is maintained that different regions may have different expected rates of return in equilibrium. The equilibrium condition simply requires that changes in the expected rate of return be the same across all regions, which equals the changes in the global rate of return. In this sense, the allocation of investment in GTEM is inefficient. There is scope for another allocation of investment (and hence the global capital stock), from a low return region to a high return region, which may raise global income and welfare. However, despite the mobility of investible funds, it is maintained in GTEM that the global capital market does not equalise the expected rates of return on investment.

GTEM is built in the Walrasian tradition. Therefore for each commodity and factor there is a competitive market. It is maintained that with fully flexible prices, markets for all goods and factors clear in each period. Commodities are distinguished by source and sold globally. Thus, they have a global market clearing condition. Capital and labor are region specific, but freely mobile across activities in search of a higher return; land is mobile within agricultural industries and natural resources are specific to each resource based industry such as coal, oil, gas, forestry and fishing. Factors are inelastically supplied and their prices are determined by the respective market demand conditions.

The savings of a regional household does not bear any relationship with the amount of regional investment; it is possible for each region to have its capital account in imbalance. A surplus leads to an accumulation of foreign debt, which needs servicing from the next period. This mechanism sets the dynamics of accumulation of net debt in GTEM. As there is a restriction on the amount of investment that a region can undertake

in any period which is set by the interactions of investment demand functions and their competition for limited global savings and a region cannot borrow for consumption, there is no Ponzi game problem in GTEM. Capital at the start of a period is given by the depreciated stock of the previous period and the gross investment undertaken over the previous period. As long as the amount of gross investment is different from the depreciation requirement, the capital stock of a region continues to change.

GTEM has a population module that links fertility and mortality with real income changes. Together with a given net migration rates GTEM projects population changes by 100-age cohorts and gender by region. With a default assumption that participation rates are constant, using the population of 15–65 years of age, changes in labor supply is endogenously determined.

In its greenhouse module, GTEM accounts for three gases: carbon dioxide, methane and nitrous oxide. In calculating CO₂ emissions GTEM accounts for combustion, fugitive emissions and industrial processes. In the case of methane and nitrous oxide, it accounts for emissions from livestock and farming activities, fugitive emissions, transport, and chemical industries. The main assumption used in the estimation is that the combustion emissions are proportional to the use of fossil fuels and other emissions are proportional to activity level. The constant of proportionality, the emission intensity is taken as a technological parameter and treated exogenously.

2.2 Modeling evolution and adoption of carbon free energy technology: some modifications in GTEMLR

Using learning-by-doing as the principle mechanism for reducing costs of new technologies in GTEMLR, Pant and Fisher(2004b) examined whether carbon-free source based hydrogen can compete with fossil fuels and become the dominant form of energy and energy carrier in this century. Some of the modeling innovations made in that paper are adapted in this paper to represent the development and diffusion of clean energy technologies. In particular, the functions representing the increasing cost of natural resource extraction in the fossil fuel sectors and learning by doing in newer energy production technologies as their scale of operation expands over time have been revised. These modifications are described in the following sub-sections.

2.2.1 Modeling increasing cost of fossil fuels

Although there are counter arguments (Odell 1999) that cannot be easily rejected, it is generally argued that as continued use of fossil fuels will deplete the existing reserve, the cost of extracting these resources will eventually rise (Gerlagh and Lise 2003). To model this process, we associate the productivity of the natural resource factor in the fossil fuel production sectors (coal, oil and gas) negatively with the cumulative quantity of the natural resource used by the industry. Let $X_{N,j,t}$ be the quantity of natural resource used by the extraction sector j , (we have suppressed the country/region index), $A_{N,j,t}$ its productivity index (it equals 1 in the base year), $\mathbf{P}_{jt}$ the vector of prices faced

by the sector and $Q_{j,t}$ the output produced by the sector at time t , then its cost minimizing input demand function can be written as

$$(1) \quad A_{N,j,t} X_{N,j,t} = F_{j,t}(\mathbf{P}_{j,t}, Q_{j,t}, A_{N,j,t})$$

and the productivity index is given by

$$(2) \quad A_{N,j,t} = [1 - \beta_j][Z_{N,j,t} / \bar{Z}_{N,j,t}]^{-\alpha_j} + \beta_j$$

where $Z_{N,j,t} = \sum_{\tau \leq t} X_{N,j,\tau}$ and $\bar{Z}_{N,j,t} = t^* X_{N,j,0}$ which also implies $A_{N,j,t} = 1$ if $Z_{N,j,t} = \bar{Z}_{N,j,t}$.

α in the above equation is a parameter to measure the speed of decline in productivity with the increase of cumulative natural resource extraction, and β is the asymptotic terminal value of the productivity when the cumulative extraction tends to infinity. The values of α and β we used are shown in table 1.

The consequence of modeling the productivity factor as given in (2) is that continued use of natural resource at a rate higher than used in the base year makes the factor less productive, or expensive in relation to other factors. Therefore, to produce the same quantity of output, more and more labor and capital will have to be employed, with a given quantity of natural resource depending on the size of the elasticity of factor substitution, which we have maintained slightly greater than unity in GETEC, as time goes by. This increases the cost of fossil fuel slowly to the users of fossil fuels – including the power generation sector. As a result, ceteris paribus, renewable technologies will become relatively more attractive compared to fossil fuel technologies.

2.2.2 Modeling learning-by-doing in renewable sector

As mentioned earlier, learning by doing is believed to be a primary reason for the decline in cost of ‘infant’ technologies, such as hydrogen production and distribution. The learning by doing process is introduced in GETEC as an endogenous improvement in input-neutral productivity in the renewable technology of the power generation sector. Recall that the input–output relation in each technology is characterised by a Leontief production function.

Let

$$(3) \quad A_{i,t} X_{i,t} = Q_t \text{ for each input } i \text{ and time } t$$

be the input demand function of the renewable, carbon free technology (note that each technology of the technology-bundle industries has a Leontief production function in GTEM). $A_{i,t}$ in equation (3) represents the productivity factor of the input i , which in other words is the inverse of the input–output coefficient. An increase in the value of $A_{i,t}$ implies increased productivity as this means that less $X_{i,t}$ is needed, without being substituted for by any other input, to produce a given Q_t .

Assume that one source of productivity growth is via learning-by-doing, meaning that the cost of production declines with accumulated experience, measured by the cumulative change in the productive capacity (Arrow 1962; Wright 1936). It is commonly believed that a doubling of the cumulative capacity leads to about a 20 per cent fall in the cost of production. In this paper we make the explicit assumption that doubling cumulative capacity, measured by output level, implies a 20 per cent fall in the requirements of all inputs, which means A_i will be about 20 per cent higher as a result of doubling of cumulative capacity.³ This process can be modeled as

$$(4) \quad A_{i,t} = \frac{1}{\eta_i + [1 - \eta_i][Z_{i,t} / \bar{Z}_{i,t}]^{-\gamma_i}}$$

where $Z_{i,t}$ is the cumulative experience, measured by the cumulative output of the new technology i , $\bar{Z}_{i,t}$ is the cumulative experience of technology i had its output remained unchanged from the base year up to year t , γ is a parameter that represents the speed at which the learning rate reaches the limit with the accumulation of ‘experience’, and $0 \leq \eta \leq 1$ is a learning parameter such that $1/\eta$ is the upper limit of endogenous productivity gain through the learning process. The values of γ and η we used are shown in table 1. Clearly in equation (4) $A_{i,t} = 1$ if $Z_{i,t} = \bar{Z}_{i,t}$ which means that if a power generation technology simply reproduces its history it does not learn; in order to learn it must be growing.

2.2.3 Modeling variable elasticity of substitution between alternative energy sources

Even in studies based on simplified models of the economy with two sources of energy supply and a single user there is a problem in modeling the substitution possibility between alternative sources of energy supply. Should the carbon free and carbon-rich sources be treated as perfect substitutes, imperfect substitutes or complements have remained an unresolved question. For example, Peck and Teisberg (1992) treat the two as perfect substitutes but impose a capacity constraint and higher costs for the carbon free technology. Goulder and Schneider (1999) treat them as poor substitutes and set the

³ In GETEC/GTEM renewables technology use only labor and capital as inputs.

elasticity of substitution very low, as is done in standard GTEM in which the default value is 0.75. Li et al. (2003) have set the values of the CRESH parameters differently for different technologies between 0.1 and 1.5. Similarly, van der Zwaan et al. (2002) assume the value to be 3. An interesting approach has been followed in Kverndokk et al. (2004), however. They have assumed the elasticity of substitution between existing fossil fuel and carbon free technology to be unity and between their aggregates and the backstop technology to be infinity. No matter what value we choose for the elasticity of substitution between the technologies, the size of the ‘estimate’ really matters.

Gerlagh et al. (2004) argue that since under a CES aggregation rule, the ratio of cost minimizing demand for carbon free energy, Y_t^N , to fossil-fuel, Y_t^F , is related to the ratio of respective prices P_t^N and P_t^F according to

$$(5) \quad (Y_t^F / Y_t^N) \approx (P_t^N / P_t^F)^\sigma$$

where σ is the elasticity of substitution between the two energy sources, the choice of base year prices, quantities and the elasticity of substitution should agree and satisfy (5). This means, we must have

$$(6) \quad \sigma = \log(Y_t^F / Y_t^N) / \log(P_t^N / P_t^F).$$

When the literature based value of Y and P for both fossil fuel and carbon-free technologies for the base year were used to calibrate the value of the elasticity of substitution, σ , they found that the value is nearly 3.

In an earlier paper by Gerlagh and Lise (2003) they used a different approach to tackle the calibration problem. They argued that the elasticity of substitution depends on the market share of the technology. In the case with two technologies, the elasticity of substitution will be low if one technology dominates and highest when both technologies have equal market shares. To model this they adopted the variable elasticity of substitution (VES) aggregator function proposed in Kadiyala (1972) and treated both technologies symmetrically. They calibrated the VES function in such a way that the resulting elasticity of substitution fell between 1 and 4.

In Gerlagh et al. (2004) it is shown (via simulations) that the required carbon tax to attain a given emission trajectory or target critically depends on the elasticity of substitution between alternative sources of energy supply. If the elasticity of substitution between the conventional carbon-rich and new carbon-free sources of energy supply is sufficiently large then the required carbon tax that can deliver the same outcome could be substantially lower compared to the case with low or no possibility of such substitution. It is also demonstrated in Gerlagh et al. (2004) that, under the assumptions of their paper, that is, with a sufficiently high elasticity of substitution, carbon free sources will almost dominate within this century as the sole provider of energy. In this case the critical question is whether the atmospheric load of the GHG produced over this century is within the tolerance limit of the climatic system. If not,

then carbon taxes could be used to bring it under control. Therefore, the size of the elasticity of substitution and the precise mechanism supporting the propagation of carbon free technologies in these models remain the subject for further examination.

2.2.3.1 Substitution between power generation technologies

GTEMLR contains multiple technologies of power generation – one of them is ‘other renewables’ (which excludes hydro).⁴ The base year share of this technology to total power generation is very small in all regions and has been chosen to represent all forms of carbon-free, including clean hydrogen, energy technologies in this paper. It is a common practice to treat these technologies as imperfect substitutes in modeling the simultaneous existence of many technologies with varying cost structures. If we use a CES function to aggregate these power generation technologies, as is done in many other studies and we assign a single value for the elasticity of substitution between all possible pairs, then for a reasonable change in relative prices it is quite clear that the output of the renewables can not rise to any significant number. This is simply because even if the relative price of renewables falls by say 10 per cent, keeping everything else constant, with a elasticity of substitution of 3, the output of renewables will rise nearly by a 30 per cent. Since 30 per cent of a small number is still small, there would be an extremely long time needed for this technology to capture a substantial market share. On the other hand, a small increment in the existing capacity of renewables may mean a large percentage increase because of the small base. For example, an addition of two solar panels when there was one is a 200 per cent increase in the production capacity and output. Hence, in order to represent the behavior of technologies with very small shares correctly, use of a CRESH function with different CRESH parameters appears more suitable than a CES function.

A cost minimizing input demand for the output of technology k , in percentage change form, subject to a CRESH aggregator can be written as⁵

$$(7) \quad x_k = q - \rho_k (p_k - \hat{p})$$

where q is the percentage change in the output (or aggregate input of the technology bundle) of the technology-bundle industry, x_k is the percentage change in the output allocated to technology k , p_k is the percentage change in the price of technology k , $\hat{p}$ is the modified share weighted (see equation (8) below) average price of all technologies and ρ_k is the CRESH parameter associated with the technology k . The average price, $\hat{p}$, is given by

⁴ Hydroelectric technology is considered as a mature technology with severe limitations to grow.

⁵ See Dixon et al. (1982, pp. 76–90) for the derivation.

$$(8) \quad \hat{p} = \sum_k \frac{\rho_k S_k}{\sum_r \rho_r S_r} p_k \quad \text{where both } r \text{ and } k \text{ range over the set of technologies.}$$

The pairwise Allen-Uzawa partial elasticity of substitution is given by

$$(9) \quad \sigma_{ik} = \frac{\rho_i \rho_k}{\sum_r \rho_r S_r} \quad \text{with } i \neq k.$$

The special feature of the CRESH function is shown by equation (9). The ratio of pairwise elasticity of substitution parameters, $(\sigma_{ik} / \sigma_{ij}) = (\rho_k / \rho_j)$ for all $i \neq k, j$ and thus the ratio remains constant for any pair k, j and hence the name. If, however, $\rho_k = \rho_j$, for all k and j , then the CRESH function becomes identical to a CES function with $\rho_k = \rho_j = \sigma$.

For a niche technology, we can see from equation (8) that changes in its price will not affect the average price in a significant way even if the price change was large. From equation (7) we can see that the percentage change in demand for its output will not be dramatically high unless the corresponding CRESH parameter is very large. But, we know that in the beginning, when the base quantity is small, a small absolute increase means a very large change in percentage terms. Hence a reasonably large value for the CRESH parameter of the niche technology is warranted. But as its market share grows to a significant number, maintaining a large value for the CRESH parameter would give undue sensitivity to this technology. The elasticity of substitution between the carbon free technology vis-a-vis any other technology will remain high while that between other fossil fuel technologies will remain low. This is especially important in models with learning by doing, as the average cost of the niche technology would be falling with the increase in cumulative capacity, other things being kept the same, and the demand for the output of the niche technology will be growing disproportionately. Therefore the CRESH parameters associated with the niche technology should have higher values in the beginning and decline subsequently. This also means that the CRESH parameters should be modelled as time dependent quantities.

To address this problem we specify the time path of CRESH parameters as

$$(10) \quad \rho_{k,t} = \rho_{k,0} + \xi_k \rho_{k,0} [s_{k,t} - s_{k,0}] [1 - 2s_{k,t}]$$

where $s_{k,t} = Q_{k,t} / \sum_j Q_{j,t}$, and ξ_k is an adjustment parameter (see table 1 for the value of this parameter). The initial value for $\rho_{k,t}$, i.e. $\rho_{k,0}$, is 2 for all conventional (fossil fuel

as well as hydro and nuclear) technologies, and 4.2, 4, 3.5 and 3.5 for the new carbon-free technology in OCED90, REF, ASIA and ALM regions, respectively.⁶

For conventional technologies, ξ_k is negative, which means $\rho_{k,t}$ goes up when their output shares fall below their initial shares and the initial shares are less than 50 per cent. Increase in these CRESH parameters allows the conventional technologies to be easily substituted with the other renewables technology as they grow and become competitive. For the other renewables technology, ξ_k is positive, which means $\rho_{k,t}$ goes up when its output share becomes higher than its initial share. Increase in the CRESH parameter for the new carbon-free technology allows it to capture increasing market share as it becomes cheaper. When the share of the other renewables technology exceeds 50 per cent, the substitution parameter declines slightly which is to allow this technology not to be too sensitive to price changes.

2.2.3.2 Use of energy commodities by firms

It was mentioned in section 2, production technologies contain nests that allow intra-energy commodity, intra-factor and energy-factor substitution in response to relative price changes and are characterised by constant returns to scale CES aggregator functions in each stage. The default elasticity of substitution between energy commodities in standard GTEM for short run simulations is 0.2. In GETEC, which typically covers more than a century, it is set to 2. This is well within the range used by previous studies. This increase also presupposes, at the same time, that machines and equipments that operate on fuel cells/electricity are available to compete with the ones that operate on coal, oil or gas (for example gas heating system versus fuel cell/hydrogen heating). In particular, it assumes that FCVs are available if there is a demand in the market to replace internal combustion engines.

2.2.3.3 Use of energy commodities by households

The other important user of energy commodities is the household sector. In standard GTEM, household consumption demand is modelled by minimising a CDE expenditure function as in GTAP (Hertel 1997). It does allow substitution between the energy commodities, but the size of the substitution within the energy group may not be comparable to the level of substitution possibilities required in modeling a transition to a carbon-free energy system, for example transition from gasoline driven cars to electric or fuel cell vehicles. This problem can be translated as the problem in household demand system of increasing the substitutability between electricity and other fuel commodities and allow households to fully substitute fossil fuels by electricity. This is so because household consumption becomes emission free if it switches from primary

⁶ The regions have been taken to match the aggregate regions used to report in the Special Report on Emission Scenarios of IPCC (Nakicenovic 2000).

energy commodities to electricity, which may be produced increasingly by zero or near zero emissions technologies.

Hence, the key problem is how to allow households to be able to substitute rapidly between conventional energy commodities and electricity to model the adoption of FCVs, should they become cost competitive. To this end, the consumer demand system in GETEC has been modified slightly and one more nest has been added to the optimizing process. Using a CRESH aggregator an energy composite is formed out of the individual energy commodities in a separate nest. Default values for the CRESH parameters within the energy nest are all set at 2. Demand for all other commodities and for the energy composite are derived by minimizing the CDE expenditure function. Given the demand for energy composite thus determined, demand for individual energy commodities are obtained by minimizing the cost of the energy composite. Once the demand for each energy commodity has been worked out from this nest, the standard GTEM allocation of demand for each commodity to the sources of supply using an Armington process has been maintained.

3 The climate module

The climate module is adopted from 5-box model of Maier-Reimer and Hasselman (1987). This model has also been used by other integrated assessment models of climate change such as MERGE (Manne, Mendelsohn and Richels 1995; Manne and Richels 2004) and FUND (Tol 2004). Only three of the most important greenhouse gases are considered in the climate module, which are carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O).

3.1 Greenhouse gas stock and concentration

(i) Atmospheric Stock of CO₂

Carbon emissions are divided into five classes (i.e. five boxes), each with different atmospheric lifetimes. The following equation estimates the CO₂ stock for each class at the beginning of year $t+1$, given the stock at the beginning of year t :

$$(11) \quad S_CO_2(b, t+1) = \kappa(b)S_CO_2(b, t) + \omega(b)E_CO_2(t),$$

where $S_CO_2(b, t)$ is the stock of CO₂ in box b at the beginning of year t , $E_CO_2(t)$ is the total emission of CO₂ in year t , $\kappa(b)$ is the yearly decay parameter (or the annual retention factor) of the stock of CO₂ in box b , and $\omega(b)$ is the fraction of total CO₂ emission which belongs to box b . The parameter values we used are shown in table 1.

In each year, the total CO₂ stock is the sum of CO₂ stock in all classes, that is,

$$(12) \quad S(CO_2, t+1) = \sum_{b=1}^5 S_CO_2(b, t+1).$$

(ii) Atmospheric Stock of CH₄ and N₂O

The following equation estimates the stock of nonCO₂ gases (i.e. for CH₄ and N₂O) at the beginning of year $t + 1$, given the stock at the beginning of year t :

$$(13) \quad S(g, t+1) = \varsigma(g) * S(g, t) + E(g, t),$$

where $S(g, t)$ is the stock of nonCO₂ gas g at the beginning of year t , $E(g, t)$ is the total emission of the nonCO₂ gas g in year t , ς is the yearly decay parameter (annual retention factor) for the nonCO₂ gas g . See table 1 for the parameter values of ς .

(ii) Atmospheric concentration of greenhouse gases

For each of the above greenhouse gases, the concentration is linearly proportional to the stock, that is,

$$(14) \quad CONC(g, t) = \theta(g) * S(g, t),$$

where $g \in GHG$ represents CO₂, CH₄ or N₂O, $CONC(g, t)$ is the concentration of gas g at the beginning of year t , and θ is the appropriate conversion parameter to convert stock to concentration ppmv for CO₂, ppbv for other gases (see table 1 for its value used). Note that S , the stock of gases is in commensurable units as well. Base year concentration (1997) are estimated at 364 ppmv for CO₂, 1690 for CH₄ and 311 for N₂O.

3.2 Radiative forcing

The equations below estimating the radiative forcing of greenhouse gases emitted are also adopted from the Houghton et al. (1997) and are similar to the equations used in the MERGE model.

(i) Radiative forcing due to increased atmospheric concentration of CO₂ is given by

$$(15) \quad RF(CO_2, t) = 6.3 \ln[CONC(CO_2, t) / CONC(CO_2, 0)],$$

where $RF(CO_2, t)$ represents the impacts on radiative forcing by the concentration of CO₂ at the beginning of year t , and $CONC(CO_2, 0)$ is the 1990 level of CO₂ concentration.

(ii) Radiative forcing due to increased atmospheric concentration of CH₄ is given by

$$(16) \quad \begin{aligned} RF(CH_4, t) = & 0.036\{[CONC(CH_4, t)]^{0.5} - [CONC(CH_4, 0)]^{0.5}\} \\ & - f(CONC(CH_4, t), CONC(N_2O, 0)) \\ & + f(CONC(CH_4, 0), CONC(N_2O, 0)). \end{aligned}$$

(iii) Radiative forcing due to increased atmospheric concentration of N₂O is given by

$$(17) \quad \begin{aligned} RF(N_2O, t) = & 0.14\{[CONC(N_2O, t)]^{0.5} - [CONC(N_2O, 0)]^{0.5}\} \\ & - f(CONC(CH_4, 0), CONC(N_2O, t)) \\ & + f(CONC(CH_4, 0), CONC(N_2O, 0)), \end{aligned}$$

where $CONC(CH_4, 0)$ and $CONC(N_2O, 0)$ are the 1990 levels of CH₄ and N₂O concentrations, respectively, and f is a function defined below:

$$(18) \quad f(x, y) = 0.47 \ln[1 + 2.01 \times 10^{-5} (xy)^{0.75} + 5.31 \times 10^{-15} x(xy)^{1.52}].$$

3.3 Temperature change

The potential temperature change is linearly proportional to the impacts on radiative forcing, that is,

$$(19) \quad \Delta PT(t) = d \times [RF(CO_2, t) + RF(CH_4, t) + RF(N_2O, t)] - Cool(t),$$

where $\Delta PT(t)$ is the potential temperature change in year t , d is the parameter for converting radiative forcing to potential temperature change (see table 1 for its value), and $Cool(t)$ is the cooling effect of aerosols which is estimated below as:

$$(20) \quad Cool(t) = c_1 SEM(t) + c_2 \ln[1 + SEM(t)/c_3],$$

where $SEM(t)$ is the world SO_x emissions (million tons of sulfur), c_1 is a parameter to measure the direct cooling effect of sulfur emissions, c_2 is a parameter to measure the indirect cooling effect of sulfur emissions, and c_3 is the natural sulfur emissions (million tons per year). These parameter values are listed in table 1. SEM for the base year is set at 69 and is assumed to remain constant over time.⁷

⁷ The product of the parameter d with $6.3 \cdot \ln(2)$ from the radiative forcing equation for CO₂ yields the value of climate sensitivity parameter used in this model. Hence the value of the sensitivity parameter is about 2.5, which measures the change in temperature for doubling of the atmospheric concentration of CO₂. Climate sensitivity can be altered by changing the value of the parameter d or the coefficient in the radiative forcing equation for CO₂.

The actual temperature change lags behind the potential temperature change because oceans take a long time to warm up. The lag process is modelled as follows:

$$(21) \quad \Delta AT(t+1) - \Delta AT(t) = \tau \times [\Delta PT(t) - \Delta AT(t)],$$

where $\Delta AT(t)$ is the actual temperature change in year t from the base year, and τ , see table 1 for its value, is a parameter to measure the time of lag between the potential and actual temperature changes (for example, $\tau = 0.025$ represents a 40 year lag).

4 A stylised damage assessment module

A simple Hockey Stick function is used to estimate the damages caused by global temperature changes. The function is derived by modifying the willingness-to-pay estimation for non-market damage in the MERGE5.1 model (Manne and Richels 2004).

The damage with the Hockey Stick function is estimated below:

$$(22) \quad \Lambda_r(t) = \{1 - [\Delta AT(t) / \Omega]^\delta\}^{\mu_r(t)},$$

where $\Lambda_r(t)$ is the region specific climate change induced economic loss factor (ELF) in year t which measures the damage, $\Delta AT(t)$ is the global average surface temperature change in year t from the base year; Ω is the catastrophic change in global average surface temperature from the reference year; δ and $\mu_r(t)$ are parameters to measure the severity of damage for a given temperature change. We have used the value of the parameter δ and Ω to determine the shape of the ELF function, $\Lambda_r(t)$ at $\mu_r(t)=2$. For any positive value of $\mu_r(t)$ we have $\Lambda_r(t) \rightarrow 0$ as $\delta \rightarrow 0$ and $\Lambda_r(t) \rightarrow 1$ as $\delta \rightarrow \infty$ and $\Delta AT(t) < \Omega$. As $\Delta AT(t) \rightarrow \Omega$, catastrophe results. Similarly, for a given finite positive value for δ , $\Lambda_r(t) \rightarrow 1$ as $\mu_r(t) \rightarrow 0$ and $\Lambda_r(t) \rightarrow 0$ as $\mu_r(t) \rightarrow \infty$. So larger values of $\mu_r(t)$ and smaller values of δ , both imply higher damages from a given temperature change. Conversely, larger values for δ and smaller values for $\mu_r(t)$ imply smaller or no damages from temperature changes that are less than Ω . The way equation (22) is specified implies that increase in global average temperature is globally damaging. It can, however, be modified to allow some benefits to some regions at small increases in average temperature. To keep the material simple we have ignored this possibility in this paper.

Following MERGE5.1 calibration, we have set $\Omega=17$ degree Celsius. We have chosen, for the purpose of this paper, $\delta=2$. By default settings it is implied that the whole economic system would collapse if the actual temperature rises by 17 degrees Celsius above the base year level. For all temperature increases below that number, there will be some economic activities going on – how much of the economic activity will be destroyed by climate change depends on the value of δ . A larger value of δ implies higher resilience – that economic activity will drop only near the catastrophic value of

the temperature change, hence the shape Hockey stick. A value of 2 for both parameters implies that for a 2 degree rise in temperature above the base year means about 4 per cent loss in economic activities and at 9 degrees, 50 per cent of the economy will be wiped out.

The time variant parameter $\mu_r(t)=2$ for all time only for the reference (or the richest) region. For other regions $\mu_r(t)$ is further defined as below to capture the vulnerability of a given country/region to climate change by linking the region's real per capita income to that of the reference region as:

$$(23) \quad \mu_r(t) = \sigma_1 + \sigma_2 \ln[I_{ref} / I_r],$$

where I_{ref} is the reference per capita real income, I_r is the per capita real income of the country/region considered in commensurable units, and σ s are an adjustable parameters to measure the effect of difference in real income affecting the vulnerability to temperature changes. This differentiation is motivated by the observations put out by Tol et al. (2000) and Tol (2003) who argue that poorer country/region have higher vulnerability to climate change relative to richer regions. Currently $\sigma_1=2$ and $\sigma_2=1$, and OECD90 is taken as the reference region. That means all other region's vulnerability is measured relative to that of the OECD90 region. It follows that $\mu_r(t) \geq \sigma_1$ for each region r .

This is where we deviate from Manne and Richel's approach to modeling damages from climate change. Manne and Richel use the hockey stick function to estimate the willingness to pay by countries to avoid non-market damages of climate change. The willingness to pay rises with income implies that $\mu_r(t) \leq 1$ for all regions and its value is unity only for the richest region. A value of zero means that the country would be willing to pay nothing. For market damages they assume that 'A 2.5 degrees temperature rise would lead to GDP losses of 0.25 per cent in the high income countries and 0.5 per cent in the low income countries. At higher or lower temperature levels than 2.5 degrees, we assume that market losses would be proportional to the change in mean global temperature from its level in 2000' (Manne and Richels 2004, p. 2). Moreover, their setting of the hockey-stick function implies that non-market damage would be about 2 per cent of GDP in rich nations at a 2.5 degree Celsius increase in the global average temperature.

In our approach, we do not explicitly model non-market damages in this paper. We, however, recognise this by assuming that loss of non-market environmental entities would contribute toward reduction in factor supplies and/or factor productivities. At our default settings OECD90 will lose about 4 per cent of its GDP in 2100 if the global

average surface temperature rises by 2.5 degrees Celsius.⁸ Loses of poorer regions will be, depending on their income relative to that of OECD90, slightly higher.

The region specific ELF, $\Lambda_r(t)$, in GETEC is currently linked to the index of total factor productivity. The difference between unity and the value of $\Lambda_r(t)$ at time t indicates the loss in productive capacity of the region by a factor of $(1 - \Lambda_r(t))$. This can also be viewed as damages in factor supplies as well or a combination of both. So in the current implementation GETEC, a rise in global average temperature means a loss in economic well-being through a decline in factor productivities. A positive value of σ_2 in equation (23) means the losses are higher for poorer regions compared to richer regions.

The advantage of linking economic damages to primary determinants of economic activities, such as factor productivity, is that it allows us to keep track of all economic accounts and preserves the properties of the social accounting matrix.

5 *Modeling international real income convergence*

Comparing real incomes or real quantities across nations is a problem that comes quite often. One such case is when one tries to model convergence of productivity or per capita real incomes across a group of nations over a long period of time. Neoclassical growth model predicts that capital poor countries will grow more rapidly than capital rich countries provided they have identical steady states. In the case of differing steady states, there is conditional convergence. In either case of convergence, comparison of real quantities is unavoidable. One may avoid this problem, however, by not using convergence hypothesis which, of course, may be desirable from both theoretical as well as empirical point of view. The use of convergence hypothesis, nevertheless, helps in economising on information.

Although we can exogenously project the future path of naturally exogenous variables in GETEC to generate a reference case, the assumption of convergence, like the ones used in IPCC's SRES, provides us with a comparable exercise. For the purpose of this paper we maintain international convergence in real per capita income of the order of SRES A1 family. As described in Pant and Fisher (2004a), we use real exchange rates to make real income comparison. In a nutshell the approach can be described as follows.

Real exchange rate, relative to the real quantity being compared, is defined as:

⁸ Tol et al. (2000) have provided a table of estimates made by various models of likely damages of climate change to various regions, in which some regions are expected to actually gain from moderate temperature increases. It must, however, be understood that they are very preliminary estimates. Our numbers are, of course, for illustrations.

$$(24) \quad E_{h/f}^R = E_{h/f}^N \frac{P^f}{P^h}$$

where $E_{h/f}^N$ is the general equilibrium market exchange rate, defined as number of home currency units per unit of foreign currency unit, P^f is the price of foreign-bundle in foreign currency units and P^h is the home price of the home-bundle in home currency unit of the *real quantities being compared*. The real quantities being compared between the countries may or may not have the same name or characteristics that is not important here, take for example the ‘GDP-bundles’. Hence, homogeneity of the commodity bundles across nations is not a required assumption. Goods can differ by sources or by destination. The question is how can we convert a given bundle of one country into units of the bundle of another country?

The approach adopted in GETEC is to find the implied *equilibrium* barter-terms of trade using *equilibrium commodity prices and exchange rates*.

It is clear that the equilibrium real exchange rate, $E_{h/f}^R$, measures the barter terms of trade between home and foreign quantities. It is the number of home ‘bundle’ per unit of the foreign ‘bundle’ being currently traded in the market. It uses the prices of the respective bundles that are being compared. This is the rate that is used in GTEC to make real income comparison.

It therefore follows that for given units of home bundle – say per capita real GDP in home units, a conversion into some commensurable units, say into foreign bundle, is required to make the comparison meaningful. Such a conversion can be made using real exchange rate. It follows from the definition of real exchange rate that

$$(25) \quad \frac{1}{E_h^R} Q_h^h = Q_h^f$$

where Q_h^f is the expression of home ‘per capita real GDP’ into units of foreign GDP-bundle.

Real income convergence stipulates that at time T

$$(26) \quad Q_h^f(T) = \omega_h Q_f^f(T),$$

where, ω_h is a parameter defining the convergence level of home real per capita income to that of the foreign (reference) country at date T.⁹

As real per capita incomes are determined by the model endogenously, the above convergence condition instead determines one productivity variable (or one instrument for convergence whatever that may be) for each converging region. For the purpose of this paper we have taken time-uniform labor productivity growth as the instrument for income convergence in each region.

6 Simulation results

For the purpose of this paper, the GTEM database has been aggregated to four regions (members of the OECD at 1990 (OECD90), reforming economies of Eastern Europe and the Former Soviet Union (REF), other countries of Asia (ASIA), and countries in Africa, Latin America and Middle-East (ALM)), 13 commodities (coal, oil, gas, petroleum and coal products, electricity, Iron and steel, non-ferrous metal, other minerals, manufacturing and food, agriculture, forestry and fishing, services and capital goods) and four factors of production (land, labour, capital and natural resources). The model is calibrated to a 1997 database. In the reference case the regional economies were assumed to have the following exogenous growth pattern per year from 1998 to 2100: land supplies in ASIA and ALM were assumed to grow at 1 per cent per annum and at 0.5 per cent per annum in OECD90 and REF. Increase in land supply can be thought of as an increase in land productivity. It could be shocked that way. In addition to these, we assumed that real per person GDP of OECD90 grows at 1.5 per cent per annum which is supported by endogenous labor productivity growth and other regions catch up OECD90's real income as follows: REF attains 90 per cent, ASIA attains 65 per cent and ALM attains 55 per cent of OECD90's real per capita GDP level at 2100 measured in OECD90's units of GDP based on endogenously determined GDP deflators and real exchange rates. The income 'convergence' is forced by region-specific time invariant labor productivity growth.¹⁰ In addition to these shocks we also assume that the global economy decarbonizes at a geometric rate of 1 per cent per annum.

⁹ In linear form the convergence condition can be written as

$$Q_h^f(T) - Q_h^f(0) = \omega_h [Q_f^f(T) - Q_f^f(0)] + [Q_f^f(0) - Q_h^f(0)] \Delta H, \text{ which further means that}$$

$$c_{-} Q_h^f(T) = \omega_h * c_{-} Q_f^f(T) + [Q_f^f(0) - Q_h^f(0)] \Delta H, \text{ where } H \text{ is a homotopy variable with}$$

exogenous shock value of $\Delta H = 1$ in all simulations forcing income convergence.

¹⁰ The choice of labor productivity as an instrument of convergent economic growth is of course not because of necessity, other forms of factor productivities, such as factor neutral productivity growth, can very well be conceived.

As the main purpose in this paper is to observe how the income convergence, the trajectory of global emissions and temperature changes are affected by the integration of damages from climate change into the model of economic system, our standard reference case is the one without the feedback modeling of damages from climate change and the alternative scenario, not quite the ‘policy’ scenario, is the one with damage function turned on. Note that, as an illustration, in this paper the damage function chosen is a highly speculative one. It endogenously reduces factor productivity uniformly across all factors and sectors in each region in response to temperature increases. Together with this climatic effect on factor productivity, annual labor productivity growth rates consistent with income convergences assumed in the standard reference case are also applied in the alternative scenarios. The income convergence is not forced as a constraint in alternative scenarios. Direct impacts of climate change on mortality rates and migration in the population have not been introduced in GETEC so far. Indirect effect on fertility and mortality rates via changes in per person real income are, nevertheless, built into the population module. As a result projection of population with damages gives an over estimate of the likely population level with climate change.

6.1 *Results of illustrative simulations: with and without the damage function*

Figure 1 presents the impacts of the projected temperature changes on regional per person real GDP. It shows the trajectories of real incomes with and without the damages for each of the four regions. In each of the regions, the trajectory of the real per person income with damages lies below the trajectory that does not take the climate change feedback into account. As a result of climate change real per person income of OECD region falls to 85 per cent, that of REF to 82 per cent, that of ASIA and ALM to 79 per cent of their respective 2100 level without the damages. In the base case REF, ASIA, and ALM converge respectively to 90, 65 and 55 per cent of OECD90’s real per person GDP at 2100. In the case with damages, however, they converge respectively to 87, 60 and 51 per cent levels.

Figure 2 presents the corresponding trajectories of emissions of CO₂, CH₄ and N₂O as well as projected temperature change over the base year level. Annual rates of emissions of CO₂ at 2100 reach 59 GtC under the base case, while they fall to 47 GtC when the feedback effects from damages are taken into account. Similarly, rate of annual emissions of methane and nitrous oxide are also lower when damages are taken into account than without. The difference in changes in the global average temperature is not that pronounced, however. It is 4.37 degrees Celsius without damages and 4.19 degrees Celsius with damages. The reason for this small difference is a 40 year long lag time to attain the full effect of increased radiative forcing due to higher concentration of GHGs into actual temperature change.

6.2 *Discussion of the results*

We reported selected results of illustrative simulations of GETEC with and without the damage function included in the model. We observed that a model that ignores feedback

from climate change projects higher income, emissions and temperature changes relative to the one that does include such feedbacks.

Underneath these results the key variables that are at work are the assumed decarbonization rate and the nature of the damage function. The decarbonisation rate limits the rate of temperature change, or climate change in general, that may result as a consequence of ‘human actions’ and the nature of the damage function limits the economic damages that might arise as a result of climate change. If decarbonisation rates are sufficiently high there will not be enough climate change to make the damages. Similarly, it is possible to have parameters of the damage function such that the resilience of the economic system is sufficiently high and therefore climate change will not produce any damages. In this case, even if decarbonisation rates are not that high, the resilience of the economic system will be able to protect itself from climate changes. In both cases, the inclusion of climatic feedback into the economic model via the damage functions becomes a redundant exercise. This zone of comfort is defined by the configuration of assumed decarbonisation rate and the ‘hockey-stick’ parameter.

One key question, then, is what is the decarbonisation process and how will this evolve over time? Decarbonisation process employed in this paper is an exogenous reduction in emission intensity of fossil fuel system and other sources of non-combustion emissions such as methane from rice and livestock production. The decarbonisation rate reflects move to cleaner use of fossil fuel by carbon capture and storage, improvement in fossil fuel combusting technologies, capture and storage of non-combustion emissions from industrial processes and change in agricultural and animal husbandry practices and technologies. Uses of carbon free energy are already built into the model. Whether such technologies will evolve and the rate of decarbonisation will be sufficiently high is a topic for further research.

The other key question certainly relates to the nature of the damage function and its parameter values. In this paper, we have employed a very simplistic function as an illustration. Real world could be quite different and regional variations could be substantial. This is another area of research which is evolving very fast (see for example, Tol 2002a,b; Tol et al. 2000; Bosello et al. 2004a,b). Our understanding on this issue will be improved over time.

Given that the values of the key parameters are reasonably good enough, integrated models will help evaluate the global and national costs and benefits of such technologies that will help guide the evolution of technological path addressing the climate change problem.

7 Concluding remarks

In this paper we have described new additions made to GTEMLR to arrive at a stylised model of global economy, trade, environment and climate (GETEC) systems. A simplified box-climate module was included with GTEMLR and a hockey-stick function was adapted from Manne and Richels (2004) to stylise economic damages that could be inflicted upon the economic system by climate changes. The parameters of the

hockey-stick function were chosen to simplify the presentation. Although very simple and speculative, the damage function provided a reasonable basis to experiment and demonstrate how an integrated climate-economy model might shed better insights when decarbonisation rates are not that high and damage function is sensitive even to small climate changes.

Table 1. List of some model parameters and their values

Parameter	Description	Value(taken from MERGE5.1)
α_j	Parameters for modeling the increasing cost of extraction of fossil fuels, see equation (2)	0.3
β_j		0.1
γ	Parameters for the ‘learning by doing’ function, see equation (4)	0.3
η		0.04
ξ_k	Parameters for the CRESH substitutions (see equation (10))	0.45 for the other renewables technology; and -8 for others
$\kappa(b)$	Annual decay parameter for CO ₂ (see equation (11))	(1;0.997;0.988;0.948;0.555)
$\omega(b)$	Fraction of total CO ₂ emission belonging to box b (see equation (11))	(0.142;0.241;0.323;0.206;0.088)
$\varsigma(g)$	Annual decay parameter for non-CO ₂ gases (see equation (13))	0.917 for CH ₄ ; 0.9917 for N ₂ O
$\theta(g)$	Parameter to convert GHG stock to concentrations (see equation (14))	0.461 for CO ₂ ; 254 for CH ₄ ; 209 for N ₂ O
d	Parameter to convert radiative forcing to potential temperature change (see equation (19))	0.572
c_1	Parameters for defining the cooling effect (see equation (20))	0.002487
c_2		0.470849
c_3		42
τ	Parameter for the lag between the potential and actual temperature changes (see equation (21))	0.025

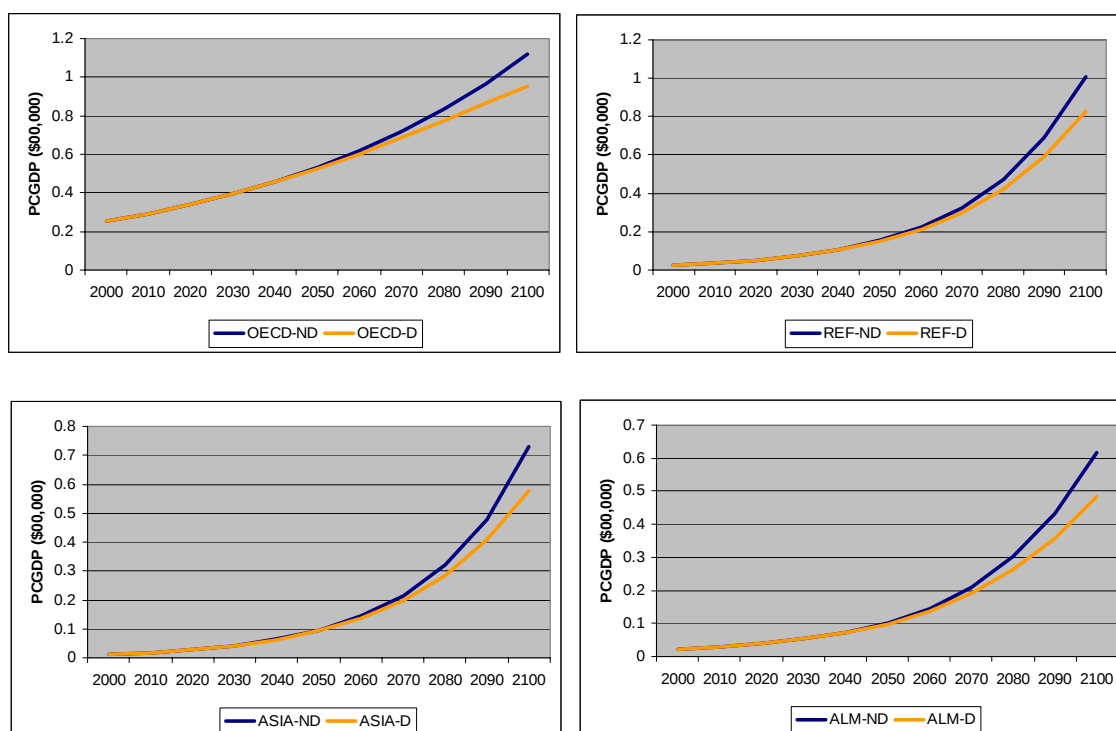


Figure 1: Income convergence with and without damages integrated

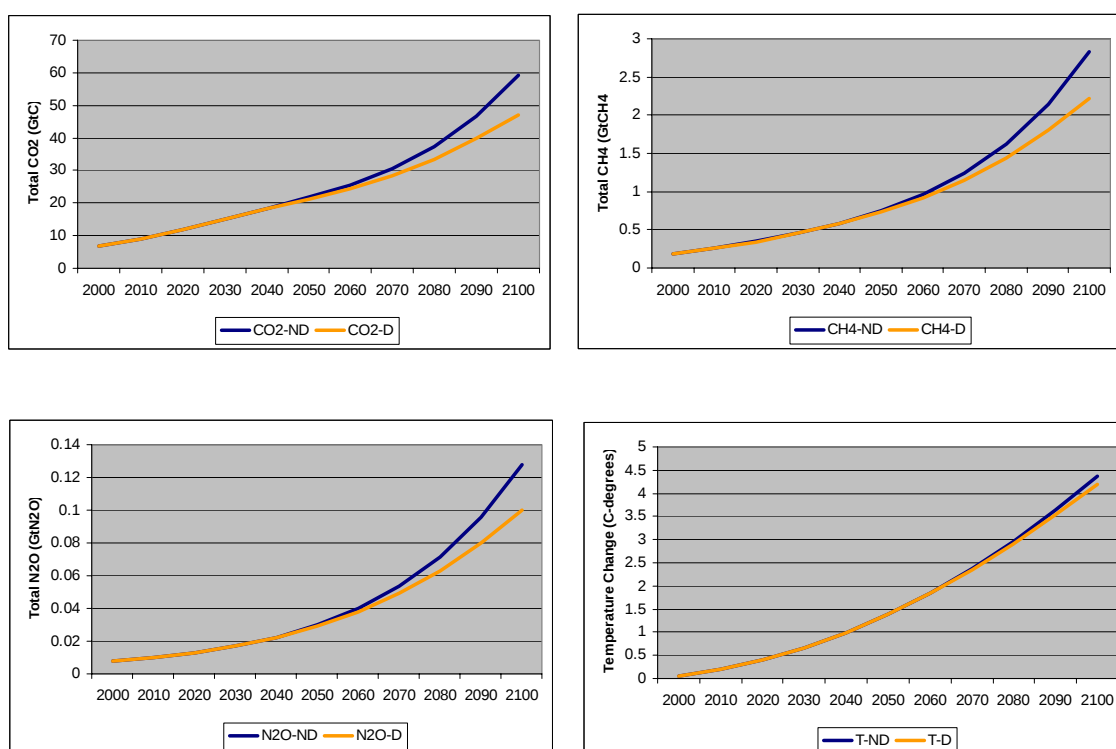


Figure 2: Emissions trajectories and projected temperature change over the century with and without damages.

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