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DOE Patent Clearance Granted

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Introduction

Real world problems rarely fall within the bounds of a single discipline. The climate change problem spans an extraordinarily large number of disciplines from earth sciences to social and political sciences. The interaction of processes described by these different fields is why climate change is such a complex issue. Keeping track of these interactions and bringing coherence to the assumptions underlying each disciplinary insight on the climate problem is a massive undertaking. A systematic approach is needed to bring about this coherence. For the past 20 years the team at Carnegie Mellon University have been developing such an approach to analysis of environmental change challenges facing humanity. *Integrated Assessment* (IA), as an interdisciplinary approach designed to provide systematic evaluations of technically complex problems. IA is not specific to the climate problem. It was first employed at CMU in 1980 to analyze the issue of Acid Rain.

Some think of IA as simply systems modeling under a new label. There are three reasons why we resist this characterization of IA:

- Systems modeling received a, well deserved, bloody nose from the Club of Rome systems approach to modeling energy futures. In their effort the human dimensions of the problem were critically under appreciated.
- Systems modeling are limited to mathematical models alone, while IA can be qualitative and informal.
- A primary goal of IA is to provide a bridge among disciplinary scientists and among the scientists, policy decision makers and the general public.

The IA effort at Carnegie Mellon can be further characterized in attempting to meet four goals:

- Characterization of the uncertainties (parametric and structural) in our understanding of the various processes leading to climate change, its impacts, and policy responses that could be undertaken.
- Characterization of the human dimensions of the climate change issue, namely cognitive aspects of detection and attribution of climate change (as opposed to variability), policy choice, formation and implementation.
- Development of new techniques for integrated assessment where climate change issues highlighted inadequacy of previous approaches.
- Explorations in disciplinary sciences were completion of the IA demanded spanning the interstices of existing disciplinary knowledge.

The core funding provided by the Department of Energy in their support for our program (DE-FG02-94ER61916, DE-FG02-95ER62105) has led to numerous publications and completed Ph.D theses. These are enumerated later in this report. In addition, DoE support was instrumental in our ability to compete successfully and become a National Science Foundation Center of Excellence in Research on Human Dimensions of Global Change. In 1997 two such Centers were created (CIPEC: Center for study of Institutions, Populations and Environmental Change at the University of Indiana – to study land use and institutions for management of public goods; and CIS-HDGC: Center for Integrated Study of the Human Dimensions of Global Change at Carnegie Mellon University).

Products

Institutional

The core support from DoE provided the foundations for the Center for Integrated Study of the Human Dimensions of Global Change. This NSF Center of Excellence involves the collaboration of 40 senior investigators from 18 institutions dotted around the world. The 8-year plan for this Center involves research on the following topics:

- The transition to less carbon intensive energy resources.
- Distributed co-generation and its implications (economics, environmental and social).
- Personal resource calculators and participatory approaches for managing energy use and carbon emissions.
- Institutional learning and adaptive capacity.
- Psychology of adaptation.
- Impacts of climate variability, extreme events and climate change.
- Health impacts of climate change.
- Land use and climate change impacts on land cover and the carbon cycle.
- Discounting and multi-generational decision-making.
- The mathematics of non-marginal change and its implications for analysis of radical policy shifts.
- Technical change and its representation in integrated assessment models.
- Development of path dependent simulation methods for analysis of climate policy formation, implementations and mid-course adjustments.

More information about these research topics and fifty other specific projects can be found on our web pages at: <http://hdgc.epp.cmu.edu>

PhD Theses

Elena Shevliakova (1996):

Application of statistical methods for modeling impacts of climate change on terrestrial distribution of vegetation

Abstract

The importance of biosphere-climate interactions for energy and moisture balances and major biogeochemical cycles is well recognized. Climate change is expected to alter the functioning and distribution of major ecosystems. These changes have been investigated using global vegetation transfer models. Typically, these models are correlative in nature, deterministic, and use heuristics in the form of process based rules to classify vegetation types for a given set of climatic and soil variables. Based on these models and future climate scenarios from GCMs, the global distributions of ecosystems in a $2\times\text{CO}_2$ are derived. In this thesis, I explore probabilistic modeling approaches that use relationships between a set of explanatory variables and the occurrence of vegetation types. Probabilistic transfer models differ from the deterministic transfer models in that they estimate the probability of occurrence of a particular vegetation type under different

climatic and geomorphologic conditions. In deterministic transfer models, on the other hand the response is Boolean in nature.

In my thesis I use two different approaches for obtaining relationships between explanatory (e.g. climatic and geomorphologic) variables and distribution of vegetation types. The first approach used a multinormal generalized logit scheme. A major drawback of this approach is that it does not provide a good approximation for the highly non-linear relationships between occurrence of vegetation types and the set of explanatory variables. Stepwise discriminant analysis was used to identify the set of climatic and geomorphologic variables, which may explain variation in vegetation types under different climatic and geomorphologic conditions. The second probabilistic approach was based on kernel discriminant analysis. I analyzed 40 different combinations of explanatory variables in the case study for Northern America. This case study shows that a 7-variables model is successful in modeling the distribution of most vegetation types with excellent degree of agreement (kappa statistic > 0.9).

Having developed the model, I explored the impact of climate change on the vegetation distribution. The usual $2\times\text{CO}_2$ climate anomaly results from the GFDL and GISS GCMs were used to complete these simulations. These simulations suggest that at most ~30% of present land cover will remain undisturbed.

**Daniel Teitelbaum (1998):
Technological Change and Pollution Control: An Adaptive Agent-Based Analysis**

Abstract

The factors which speed and slow technological innovation have been of interest to policy makers since at least the mid 1960's. Since that time, many theoretical models of innovation at the firm level and at the industry level have been proposed. Due to limitations in computational complexity, nearly all of these models have assumed a single, representative firm type. Very few have systematically investigated the implications of markets with a variety of firm types. With increases in computing power and the advent of agent-based modeling, interactions between agent types can now be explored. In this thesis, a computational model of innovative firms in competitive markets is presented. Firms devote resources to R&D which can lead to new, improved products allowing firms to steal market share from their competitors. Initially, two types of firms, differentiated by the strategies they use in pursuing new innovations, are allowed to coexist. One type pursues exclusively radical innovations, while the other pursues exclusively incremental innovations. It will be demonstrated that under certain conditions, a synergy exists between firms of different types which allows heterogeneous populations of firms to earn more than homogeneous ones. Later, firms capable of making optimal decisions are added.

Next, pollution and a government which monitors, taxes and limits pollution are added. It will be demonstrated that the model agrees qualitatively with established results from the economics of pollution control literature. In addition it will be shown that

government can control pollution more effectively when firms are given time to prepare for the onset of pollution regulations rather than being surprised by them. Finally, an endogenous pollution regulation mechanism is proposed. It is demonstrated that the effects of pollution controls can vary widely across firm types.

**J Jason West (1998):
Studies in natural and human system response relevant to global
environmental change**

Abstract

Part One - Marginal PM_{2.5} and Marginal Direct Climate Forcing: Nonlinear Responses to Changes in Sulfate Concentration

Fine airborne particulate matter (PM_{2.5}) and direct aerosol radiative forcing may be nonlinear functions of sulfate concentration, due to interactions between sulfate and other inorganic aerosol components. In contrast to average measures of forcing, we define marginal forcing as the local change in forcing from a small change in sulfate concentration. Using a nonurban continental aerosol, we estimate that the marginal forcing may vary strongly with sulfate concentration, from -550 to +20 W (g S04)⁻¹ at 80% relative humidity. Average measures of forcing may therefore significantly overestimate the effect of changes in sulfate concentration.

Assuming thermodynamic equilibrium, we estimate that the conditions for a nonlinear response to changes in sulfate concentration are common in the eastern US in winter, and are uncommon in summer. Decreases in sulfate concentration may therefore increase aerosol nitrate and may be up to 50% less effective than expected at reducing the annual average PM_{2.5}. Considering this nonlinear aerosol mass response and the dependence of direct forcing on other geographically-variable parameters, the annual average marginal forcing is not expected to vary over land masses by more than a factor of four, while in many areas of interest, it will vary by less than a factor of two.

Part Two - Storms, Investor Decisions, and the Economic Impacts of Sea Level Rise

In addition to damaging coastal property directly, erosion accelerated by a climate-induced sea level rise may also increase the vulnerability of property to storm damage. We present methods of assessing the economic impacts of sea level rise, using the bounding cases of no foresight and perfect foresight. We use a disaggregated analysis which includes the effects of storms, and model market valuation and private investor decisions dynamically. Using data from the National Flood Insurance Program and a hypothetical community, we estimate that the increase in storm damage due to sea level rise is small (< 5% of total sea level rise damages), but could become more significant under other reasonable assumptions or where dune erosion increases storm damage.

Niel Strachan (2000): Adoption and supply of a distributed energy technology

Abstract

Technical and economic developments in distributed generation represent an opportunity for a radically different energy market paradigm, and potentially significant cuts in global carbon emissions. This thesis investigates distributed generation along two interrelated themes:

1. Early adoption and supply of the distributed technology of internal combustion engine cogeneration.
2. Private and social cost implications of distributed generation for private investors and within an energy system.

Engine based cogeneration of both power and heat has been a remarkable success in the Netherlands with over 5,000 installations and 1,500MWe of installed capacity by 1997. However, the technology has struggled in the UK with an installed capacity of 110MWe, fulfilling only 10% of its large estimated potential. Site level data was obtained for all engine cogen adoptions in both countries from 1985 through 1998, supported by actual data on costs, operating experience and energy tariffs. Institutional differences between the two countries were investigated to explain this dramatic difference. Two potential explanatory factors were not pursued in detail: the role of adopter networks, and organizational decision making under falling and volatile energy prices.

An engineering economic simulation model of engine cogen investments was developed for the UK, and extended for the Netherlands. The major result of the investment model was the existence of a minimum economic size threshold, largely due to scale invariant maintenance costs. For the UK, a 140kWe unit gave a 50:50 probability of a positive NPV on investment. Therefore, the majority (>60%) of early UK adoptions of this distributed technology were questionable economic investments. In the Netherlands, lower capital and maintenance costs, together with reduced grid connection costs, reduced the minimum economic size threshold to 100kWe. Available subsidies brought this size threshold even lower to 70kWe and improved returns for all units.

A regulatory policy implication to overcome this minimum size threshold is to facilitate installations serving multiple sites for consistent base electricity and heat loads, through improved electricity buy-back rates. A technological policy implication is to seek distributed energy technologies with minimal maintenance requirements for economic operation and hence adoption.

In the UK, the capital risk barrier could be overcome by the use of readily available supplier financing. However, the majority of early units were below our minimum economic size threshold. Why would suppliers invest their own capital in these units? Our analysis suggests that two quite different marketing strategies were followed. The former, employed by the firm that boosted its market share, is to install larger units, and enjoy both capital sales revenue and long term revenue from a premium on electricity generation if the unit is supplier financed. This revenue stream is dependent on size. The latter marketing strategy, employed by the firms that struggled to maintain market share,

is to install units possibly under a minimum economic size threshold and enjoy long term revenue from maintenance contracts. This revenue stream is largely independent of size. A policy implication for government technology information programs, is to focus on the characteristics of adopted units rather than on the overall number of installations.

Public subsidies undoubtedly aided engine cogen diffusion in the Netherlands. However, despite a lower economic size threshold, larger and more profitable units were installed in the Netherlands. This was due to innovative operation of distributed cogeneration, aided by the proactive role of distribution utilities. Utilities were substantially involved in joint ventures with engine cogen suppliers and users, offering improved electricity buy-back tariffs and lower connection costs. This facilitated flexible operation of distributed generation. Larger installations were sized for on-site heat requirements with electricity export providing revenue, and could be utilized in management of energy networks. Distributed cogen became the most successful tool for CO₂ reductions under the Netherlands National Environment Plan.

Joint venture benefits for distributed cogen extended into liberalized markets in both the UK and Netherlands. Utilities are important joint venture partners for engine cogen suppliers in a liberalized market to negotiate reasonably priced back-up power prices, especially in times of high demand, provide capital for energy services agreements and to offer name recognition in a competitive energy market.

Substantial public funding of distributed cogeneration was undertaken in both the Netherlands and UK. Was this an appropriate expenditure of public revenue?

We compared the fuel use, private and social costs of three distributed and three centralized gas-fired generation technologies to meet different demand requirements over a range of heat to power ratios (HPR). Supplemental heat was provided by boiler plant. On fuel use alone, we compared distributed generation to CCGT plus heat boiler plant, fuel cells are more efficient if the $HPR > 0.3$, gas turbines if $HPR > 0.7$, engines if $HPR > 1.4$, and micro-turbines if $HPR > 1.7$. Comparing decentralized technologies to gas turbines, fuel cells are always more efficient, engines are if $HPR > 2$ and micro-turbines are if $HPR > 2.4$.

Comparing total private costs for electricity production only ($HPR=0$), centralized CCGT plant is the lowest cost, with gas turbines second. Micro-turbines are the best distributed technology, with fuel cells becoming uncompetitive due to high capital costs. However, when we compare at an HPR of 2.3 (which is the average UK demand) and utilize boiler plant as supplemental heat, a very different picture emerges. Now distributed generation (micro-turbines and engines) are superior and gas turbines are also competitive. Micro-turbines have total private costs of supply which are only 56% of the current UK technology mix. This supports promotion of distributed generation.

Comparing total private costs plus social costs from CO₂, SO₂, and NO_x and CO emissions, micro-turbines are the lowest cost technology, especially at higher heat loads. Engines are also very competitive providing their NO_x and CO emissions are controlled. Gas turbines also offer low overall costs especially at lower heat loads. Centralized plant

suffers due to high distribution costs and energy losses, although cogeneration improves their performance.

However, electricity and heat outputs from distributed cogen may not be matched to the heat and electricity requirements in an energy system. Therefore, a static Mixed Integer Linear Programming (MILP) optimization model was developed to minimize total costs for meeting the electricity and heat requirements of two US states with different seasonality and HPR characteristics.

Aggregation of sectoral loads gave savings over the 15 year time horizon of 7.5% for New York and 11.3% for Florida. Consistent loads ensure that fewer plants are required and these can be operated for longer and thus at reduced cost. An aggregated demand with an HPR that matches the output from distributed cogen (HPR from 1.5 - 2.5), maximizes the savings from distributed cogen.

As distributed cogen (engines) were the lowest cost technologies, we compared this solution to use of conventional electricity-only and heat-only plant. With no distributed cogen, costs increases are substantial at 36% for New York and 27% for Florida. New York's greater heat demand allows more heat output from engines (electrical efficiency is only 29% HHV), to be utilized. Extending the distributed cogen vs. conventional supply comparison to natural gas usage, the greatest reductions are when the demand requirements match the outputs (i.e. HPR) of distributed cogen technologies. For New York and Florida, overall reductions in gas consumed are 32% and 35% respectively. Peak demand requirements are less well matched, although even at maximum heat demand (HPR=4.4) when a gas network is run at maximum capacity, savings of between 10-15% are realized. Savings at peak demand times can be improved by having a mix of electricity and heat-only technologies in the solution set, to alleviate excess production of heat or electricity from cogen plant.

The cogen vs. conventional supply comparison is further extended to look at social costs from production of CO₂, SO₂ and NO_x. Distributed cogen delivers CO₂ savings with only a small increase in NO_x emissions costs. If coal steam turbines are in the conventional supply mix, these increase CO₂ and NO_x emission costs, with substantial SO₂ externalities. Considering social costs from pollutant emissions increases the monetary savings of distributed cogeneration to meet a system's electricity and heat requirements. For social plus private costs and aggregating sectors in New York state, the optimal distributed cogen solution is 75% of that using conventional supply technologies, and 62% of the solution using coal steam turbines in the conventional technology mix.

The optimal runs for distributed cogen vs. conventional supply technologies were used to calculate an appropriate capital subsidy for distributed cogen. Considering private cost savings over 15 years, appropriate subsidy of optimal technologies range from \$497 - \$654 per kW. As plant and network capital costs of engine cogen are \$1,125 per kW, this is an average capital subsidy of 51%. If social costs are included, this range rises to \$623 - \$785 per kW, and if coal fired centralized plants are considered, then subsidy level rises

again to around \$980 per kW. These subsidies valuations only apply to our optimal solution. (i.e. only up to the optimal number of distributed cogen units [in the correct application]). Subsidy levels are higher in New York as its demand (heat dominated) is better matched to distributed cogen. Thus fewer units are required and the subsidy per unit is higher.

Actual capital subsidies offered for engine cogeneration were \$220 per kWe (20% of capital cost) by the Dutch and \$180 per kWe (16% of capital cost) by the British government. These subsidies are justified by the results of our model. Even if we apportion all the revenues from a Netherlands levy on energy prices for all CO₂ reduction measures as an upper bound to the subsidy, this works out at \$570 per kWe. This upper bound figure is still justified by the model results.

Ongoing works seeks to investigate issues in the transition to a system of distributed cogeneration. In our zeroth order analysis of stranded generation assets we show these to be dependent on the vintage of plants and relatively small given the age of existing US plant. Three scenarios were investigated: demand increase, existing plant retiral and demand increase plus retiral, for changed load factors of existing plant and possible stranded assets. Steam turbines and boiler plant saw their optimal load factor decreased. However, gas turbines originally for peak electricity needs, realized large increases in load factor and a resultant increase in valuation. This increased valuation outweighed losses in other plant. Averaged load factors for all existing plant increased by ~7%, ~25% and ~33% respectively in the three scenarios as more and more engines were adopted. Therefore, this zeroth order analysis suggests that stranded generation assets are not an issue.

Matthew Oravetz (ABD):

Aggregate Energy Efficiency of the Economy: history, and future

Abstract:

Energy intensity of the economy is often modeled as being determined by the combined effect of a price elasticity of demand, and an exogenously specified, technical change parameter denoted as the "Autonomous Energy Efficiency Improvement" (AEEI). Here, we study historic aggregate energy efficiency trends for the US from 1954-94. We show that the historic trends are inconsistent with an autonomous model of improved energy efficiency. As an alternative we propose a model of price induced efficiency, π , in which aggregate energy efficiency trends respond to changes in energy prices beyond price elasticity of demand ϵ .

Our back-casting exercise reveals that the aggregate price elasticity of energy demand of the US economy has been declined by roughly 15% over the past four decades. But beyond this decline, bringing back-casts and history into close correspondence requires π to change sign before and after 1974. Before 1974, after accounting for price elasticity of demand, the economy was growing less energy efficient. After 1974, after accounting for the price elasticity of demand, the economy was growing more energy efficient. Furthermore, since 1984, the rate of energy efficiency gain has been declining.

When projections of long-term energy use are compared, those with a price induced energy efficiency formulation generate significantly more price sensitive energy use and emissions trajectories. When in the business as usual scenario energy prices are expected to be rising, climate policies involve lower shadow carbon prices with π than with AEEI formulations. In scenarios where energy prices are relatively flat, energy intensity rises leading to CO₂ emissions far higher than standard business as usual projections utilizing AEEI assumptions.

Peer Reviewed Papers

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Teitelbaum, D. and H. Dowlatabadi (2000). "A Computational Model of Technological Innovation at the Firm Level." Computational and Mathematical Organization Theory 6(3): 227-249.

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West, J. J., A. S. Ansari, et al. (1999). "Marginal PM2.5: nonlinear aerosol mass response to sulfate reductions in the eastern US." Journal Air & Waste Management Association 49(12): 1415-1424.

West, J. J., C. Pilinis, et al. (1998). "Marginal direct climate forcing by atmospheric aerosols." Atmospheric Environment 32(14/15): 2531-42.

West, J. J., H. Dowlatabadi, et al. (2001). "Storms, investor decisions, and the economic impacts of sea level rise." Climatic Change 48: 317-42.

Models

The Integrated Climate Assessment Model (ICAM) version 3

Just as George Orwell observed that down on the Animal Farm not all pigs were equal, in the world of climate change assessment, not all models are the same. Models are often developed after the key questions being explored have been identified. Although sometimes existing models are "extended" to address larger or more specific questions than before. However, beyond identification of the key issues lies the challenge of whether such questions are inherently answerable. Reflection on key features of the problem and the state of current knowledge can often help us evaluate whether a question is answerable. All too often, while an assessment can have higher precision, this comes at a price in terms of the quality of the empirical evidence needed to specify the model and the processes governing its dynamics. Thus, a seemingly more detailed assessment is reliant upon gross generalizations in order to specify the key processes.

Some issues of heterogeneity are critical to the resolution of key questions. For example, the distribution of climate change and policy impacts are critical to many questions in such assessments. However, our ability to project global change phenomena at the level of specific industries and localities is severely limited. Nevertheless, all too often precision is mistaken for accuracy. For example, it is not terribly relevant whether the economy is depicted with 5 or 50 sectors in a trade model, when the underlying dynamics of trade advantages are unknown. In the past two years, a number of trade models have been developed to predict the impact of climate policy on competitiveness. The argument being that if climate policy is only adopted by Annex 1 countries, their products will be placed at a competitive disadvantage. It is feared that the Annex 1 countries will have more expensive products, that markets would be lost to competitors, with ensuing domestic job losses and a decline in the standard of living. The positive outcome is that standard of living in non-Annex 1 countries would rise. However, the products will now be produced by countries who are not bound by a climate treaty to limit their GHG emissions, and often have more carbon intensive economies.

Consequently, the cost of the policy is far higher than the mitigation costs. Furthermore, the rising standard of living in the non-Annex 1 countries is likely to be reflected in increased fossil fuel use, and there is a real possibility that the GHG control policy can lead to a global increase in GHG emissions.

The key determinants of whether the narrative above is accurate is not how many sectors of industry are modeled, it is what determines market share and the accuracy with which the relative costs of production in various regions of the world are projected.

However, many trade & climate policy models involve assuming that the productive activities in the rest of the world look like the US or other OECD countries (because we only have sufficient data from these nations). This is clearly not the case. What is needed is an understanding of China's or India's trade advantage, and how it may evolve through time. Unfortunately, the evolution of current analyses has been to increase the detail in specification of industrial sectors, and geographic regions with each release of more powerful computers. If the fundamental uncertainties in projection of trade patterns were recognized, the folly of this evolutionary pattern, and fragility of insights generated using such models would be evident to all.

The Modeling Environment

Explicit treatment of uncertainty is one of the distinguishing features of ICAM. The other is the graphic user interface, which permits even the casual user to understand the interactions between different elements of the climate issue from simply looking at the model on the computer screen. Our desire to develop such models is long-standing, and had earlier led to the development of a software environment called DEMOS. Thus, the ICAM family of models were developed using DEMOS, and its more advanced successor Analytica™. When a user tries to run the ICAM model she will be faced with an opening screen which warns her that the model is not a forecasting tool. Then, she will see the model outline as it appears in Figure 1.

It is clear from the model, that demographic and economic processes lead to energy use and emissions of greenhouse gases and aerosols. These impact composition of the atmosphere, and bring about climate change. Such climate change leads to various impacts which in turn can affect socio-economic and other processes. It is possible to make interventions in economy, in energy use, and in emissions. In their turn, economic factors, climate change, and climate impacts can influence the initiation and path of interventions.

The graphic user interface makes it possible to show the nested nature of the problem and its complexity. For example, within the demographics module there is a choice between two demographics models, a simple model with a single age cohort, or a complex model with full linkages to the other variables in ICAM and full age and gender specification. Within the complex demographics model, there is a model of fertility, infant mortality,

and life expectancy. Each of these is in turn specified by a series of equations. The parameters to these models are uncertain and their value ranges are described probabilistically from longitudinal and cross sectional data - see Figure 2.

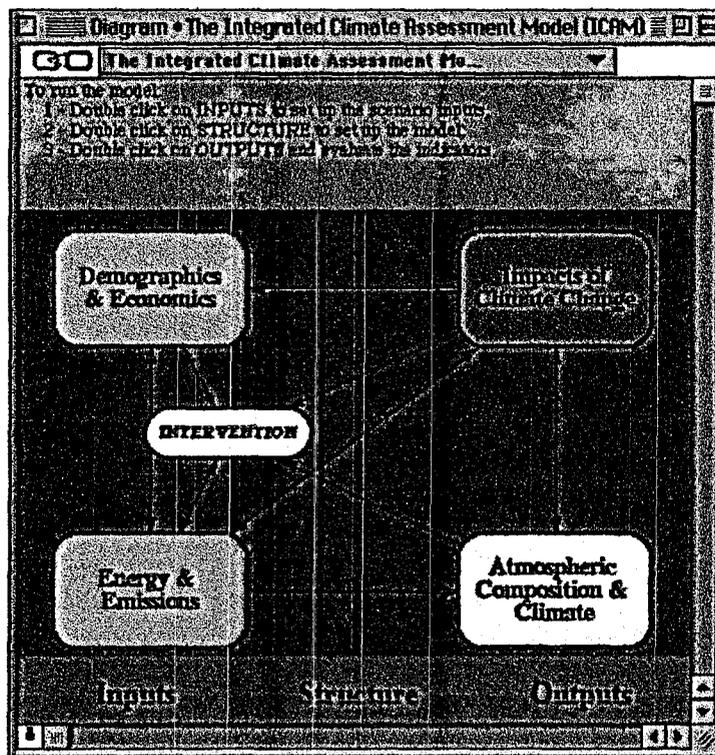


Figure 1: The diagram above is the model structure for ICAM-3. The graphical user interface conveys the relationship between the different elements of the model. The arrows show how processes within different modules influence one another.

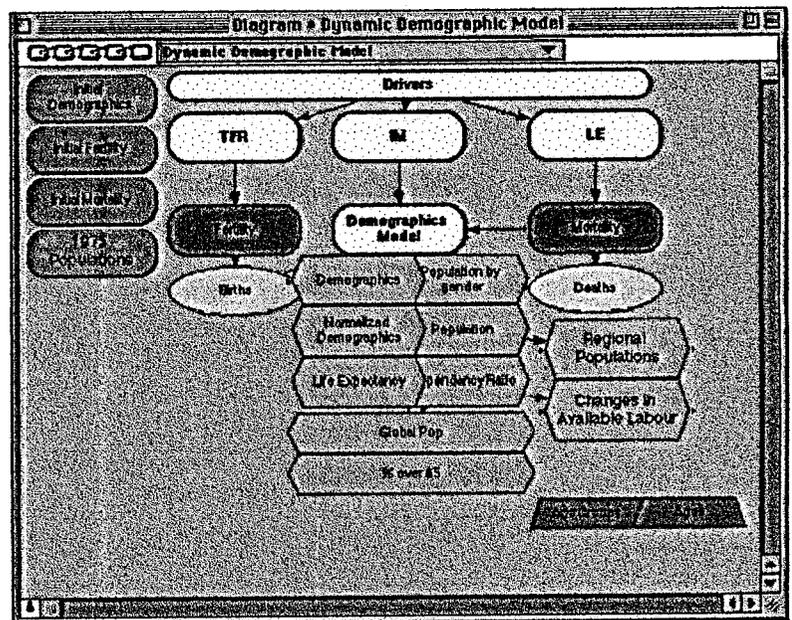
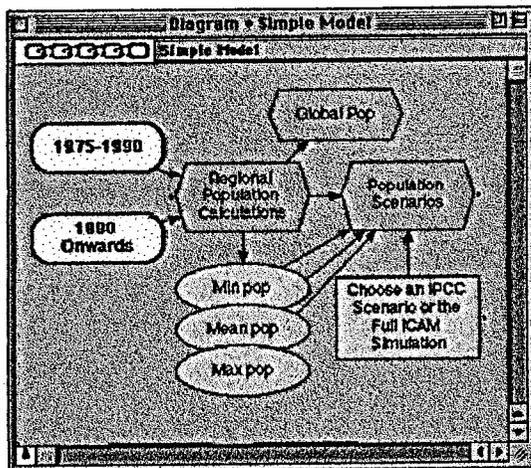
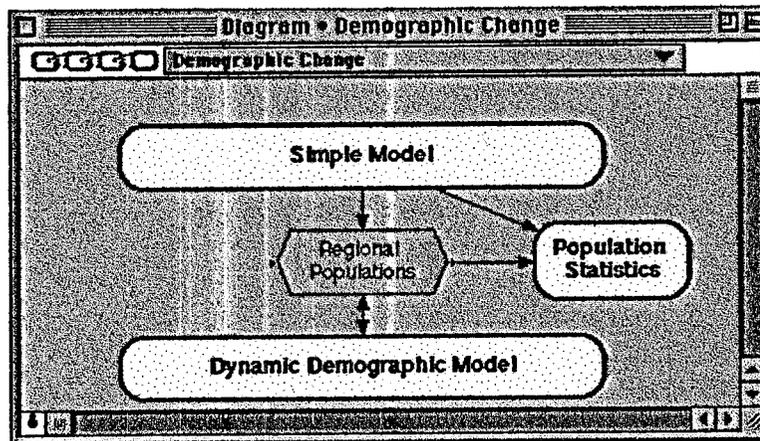
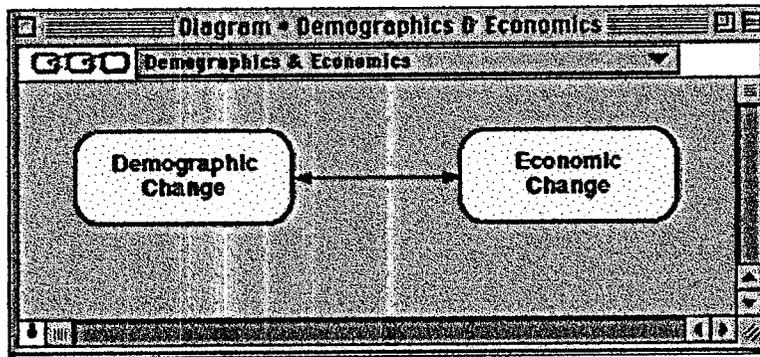


Figure 2: The "Demographic Change" module contains two models with different levels of complexity to choose from. A simple model is single age cohorts replicating the gross features of the UN population projection ranges. A more complex dynamic model that has 5 year age cohorts and is estimated from socioeconomic data generating a full range of probabilistic demographics with age structure.

Successive Generations of ICAM

In the design of ICAM uncertainties and the need to represent heterogeneous features of the global change problem have led to a series of evolutionary changes in the resolution of the various generations of the model. A number of the key features of this evolutionary process are tabulated in Table 1.

Temporal resolution

The initial time resolution for ICAM-1 was 25 years. This time constant is suitable for modeling the dynamics of processes which are relatively slow and have long lag times. We were interested in exploring the links between socio-economic development and climate change due to GHG emissions. So, carbon-cycle and climate dynamics determined the appropriate temporal resolution. In the next generation of models, the human decision-making and intervention process was an important aspect of the explorations and these occur on a much more frequent basis. Hence, the models' temporal resolution was increased to a 5-year time step. Throughout, processes with faster time constants than the time-step of the model have been approximated using numerical parameterizations.

Spatial resolution

The initial spatial resolution for ICAM was two world regions. One region with more wealth, more emissions, and lower population and economic growth rates. The other region with less wealth and more rapid economic and population growths. The geographic location of these two regions was used to highlight the different expected climate change close to and far from the equator. So, the model was used to highlight the demographic and socio-economic heterogeneity of a very simplified world. The two regions bore different responsibilities for the precursors to climate change. In addition, the two world regions highlighted of contribution to, and impacts from climate change. In this model, even the energy sector was simplified to one fuel, with the policy lever representing the opportunity to manipulate its carbon content.

Aerosols required a more detailed energy model

Along with the recognition of the importance of aerosols, it became clear that the spatial specification needed to capture the regional pattern of aerosol emissions and loading. Unlike GHGs, aerosols cannot be treated in terms of a global impact. The bulk of their impact is regional. Hence any new version of ICAM hoping to address aerosol emissions

needed to have regions defined in terms of aerosol emissions and transport. This led to the development of ICAM-2 with seven world regions. These regions were chosen to highlight the diversity in fuel sulfur contents and background aerosol concentrations (much lower in the southern hemisphere). In addition to the need for greater spatial disaggregation in the model, there was also a need to have a better specified model of primary energy supply. Thus, ICAM-2 was developed with coal, oil, gas, and non-fossil fuels all specified explicitly. Each of these fuels represents a different vector of carbon and sulfur contents. The climate change assessment problem definition now required explicit consideration of the fuels and implications of climate policy on fuel choice, as well as, on energy conservation.

The inclusion of sulfur emissions in the model, has an added benefit that we can begin to assess the implications of climate policy on local air pollution and the impact of local air pollution controls on regional climate change. The ancillary health impacts of climate policy through reduction of urban air pollution is also represented in ICAM-3.

Impacts

The other dimension in which various ICAM models have expanded is the categories of impacts considered. In ICAM-1, we recognized the importance of market and non-market impacts of climate change. Thus, the model contained both categories of impacts and emphasized the importance of both the magnitude and rate of climate change as determinants of realized impacts. However, this was insufficient in highlighting the impacts faced in coastal regions. Thus, in ICAM-2, we included regional estimates of the impacts of sea level rise with and without investments in coastal protections. The impacts included: economic losses, inundation of land, and forced migration of populations.

In ICAM-3, an even broader range of impacts were included. Three new impact categories were developed: (i) impacts of global change on un-managed land cover; (ii) impacts on human health; and, (iii) impacts on profitability of agriculture. The land cover impacts allow us to have an active biosphere carbon-cycle. The human health impacts module permit us to calculate the direct and indirect impacts of climate policy. Human health effects are seen as one of the more persuasive factors in galvanizing the public in support of climate policy.

Geo-engineering

It is rare for a model to lose a significant feature while evolving. However, when we developed ICAM-1 we were interested in evaluating the relative costs and efficacy of geo-engineering, as well as adaptation and mitigation options. These analyses highlighted the low cost of stratospheric aerosols, and the limitations of enhanced carbon sequestration. We saw no need to revisit these analyses, given the computational burden of retaining geo-engineering as a policy option orthogonal to mitigation and adaptation. Hence, in later versions of the model, these have been dropped altogether.

Decision-making

Another area of extensive change in ICAM-3 is which aspects of climate policy decision-making are exogenous to the model, and which are endogenous. ICAM is a simulation model. Most other integrated assessment models are developed as optimization models where the efficacy of one or other strategy can be studied according to their performance along optimal paths. However, the Analytica™ modeling environment does not permit optimization. The software platform is also not capable of nested sampling. Thus, the probabilistic simulations are achieved by examining the ensemble of many deterministic simulations generated by sampling from pre-defined probability distributions for key parameters.

In the first generations of ICAM we used this feature to generate probability distributions for key outputs from the model, given an exogenous policy. For example, consider the decision to have a moderate carbon tax to limit emissions. The level of this tax would be decided outside the model, and a tax trajectory (through time and for each region) would be prescribed. Then, the model would generate a range of emissions for each region. The same level of tax would bring about anything from a rising to a rapidly falling emission projection, because of uncertainty in base emission rates and in the response of the energy-economy to the tax. But in sequential decision-making, the decision-maker is able to monitor progress towards their objective and modify the intervention to steer the system towards their goal. In optimization models, this is achieved by setting constraints for the model, and solving these at least cost. It was necessary to develop a similar capability for ICAM.

In ICAM-3 the user can still define an exogenous tax profile and examine its implications for future emissions. However, we have now introduced the notion of adaptive control in the model. The users can now specify their goals, and “agents” within the model initiate and manage the steps needed to approach the pre-specified goal. This has made it

possible to explore the features of a dynamic learning-by-doing environment. Via this approach we can explore the behaviorally realistic feasibility of different goals and strategies for climate policy. The solution method highlights the limitations imposed on successful problem management by imperfect observational skills. Thus, unlike optimization models, there is always a chance that feasible goals will not be met, simply because the dynamics of learning and response would not permit appropriate mid-course corrections.

Documentation

A book on ICAM is under preparation and is scheduled for publication in 2001. This book describes each module in the model, explaining the challenges in developing a useful model at this scale and uncertainties in parameter values and model structures. The book then offers examples of how ICAM can be used to study various aspects of climate change, from impacts and adaptation through monitoring, policy design, and policy implementation.

Public Access

ICAM has been developed with the public in mind. The graphic user interface is there to help users better understand the key processes and interactions (as they are modeled). ICAM can be downloaded by any user from our web pages (<http://hdgc.epp.cmu.edu>). The model has extensive self-documentation and users can contact the developer (Dowlatabadi) to discuss their questions and concerns.

Table 1. Evolution of the ICAM Family of Models.

	ICAM 1.0	ICAM 2.0	ICAM 3.0
Temporal resolution	25 years	5 years	5 years
Temporal period	1975-2100	1975-2100	1975-2100
Spatial resolution	2 world regions	7 world regions	12 world regions
Scope	climate change	climate change	climate change
Demographics	probabilistic version of UN projections	same as 1.0 + birth rates and mortality linked to welfare	full demographic model with age specificity with dynamics driven by four socio-economic factors
Energy supply	single fuel	gas, oil, coal, non-fossil with endogenous pricing	2.0 + endogenous discovery in response to scarcity, and economics of learning
Energy demand	fixed Autonomous Energy Efficiency Improvement (AEEI)	dynamic "AEEI" responding to energy policy	2.0 + economics of learning, and endogenous technical change in response to prices.
Carbon cycle	"neutral biosphere"	same as 1.0	active biosphere with landcover responding to climate change and landuse patterns
Greenhouse gases	CO ₂ , CH ₄ , N ₂ O	same as 1.0	same as 1.0
Aerosols	none	Sulfate, organic carbon, and elemental carbon	same as 2.0
Mitigation options	command and control	command & market mechanisms via a nested inter-fuel substitution / demand model	2.0 + technologies for removal and disposal of CO ₂ .
Adaptation	none	Foresight, and adaptation included in aggregate impact modules	2.0 + process-based impacts including capital turnover & technological change
Impacts	market and non-market aggregate impact functions	same as 1.0 + sea level rise	2.0 + ecosystem change + human health effects due to urban air pollution, and change in welfare.
Geo-engineering	atmospheric aerosols & enhanced carbon sequestration	none	none
Decision-makers	passive agents	policies are prescribed by the user	adaptive interacting agents are employed to pursue solutions towards user specified goals.
Distribution date (number of copies sent out)	January 1993 (≈10)	January 1995 (>50)	January 1999.