# CHAPTER 2

# Models Used in This Research

## OVERVIEW OF THE MODELS

The computer models used in this research are referred to as integrated assessment models because they combine, in an integrated framework, the socioeconomic and physical processes and systems that define the human influence on, and interactions with, the global climate. They integrate computer models of socioeconomic and technological determinants of the emissions of GHGs and other substances influencing the Earth's radiation balance with models of the natural science of Earth system response, including those of the atmosphere, oceans, and terrestrial biosphere. Although they differ in their specific design objectives and details of their mathematical structures, each of these IAMs was developed for the purpose of gaining insight into economic and policy issues associated with global climate change.

To create scenarios of sufficient depth, scope, and detail, a number of model characteristics were deemed critical for development of these scenarios. The criteria set forth in the Prospectus for this research led to the selection of three IAMs: IGSM, MERGE, and MiniCAM. These three are among the most detailed models of this type of IAM, and each a has long history of development and application.

- **IGSM** of the Massachusetts Institute of Technology's Joint Program on the Science and Policy of Global Change is an Earth system model that comprises a multi-sector, multi-region economic component and a science component, including a two-dimensional atmosphere, a three-dimensional ocean, and a detailed biogeochemical model of the terrestrial biosphere (Sokolov et al. 2005). Because this research focuses on new emissions scenarios, elements of the scenarios emerging from the economic model component of IGSM, the Emissions Prediction and Policy Analysis (EPPA) model (Paltsev et al. 2005), are featured in the discussion below. EPPA is a recursive-dynamic computable general equilibrium (CGE) model of the world economy and greenhouse-relevant emissions, solved on a five-year time step. Previous applications of IGSM and its EPPA component system can be found at http://web.mit.edu/globalchange.

- **MERGE** was developed jointly at Stanford University and the Electric Power Research Institute (Manne and Richels 2005). It is an inter-temporal general equilibrium model of the global economy in which the world is divided into nine geopolitical regions. It is solved on a ten-year time step. MERGE is a hybrid model, combining a bottom-up representation of the energy supply sector with a top-down perspective on the remainder of the economy.[1] Savings and investment decisions are modeled as if each region maximizes the discounted utility of its consumption, subject to an inter-temporal wealth constraint. Embedded within this structure is a reduced-form representation of the physical Earth system. MERGE has been used to explore a range of climate-related issues, including multi-gas strategies, the value of low-carbon-emitting energy technologies, the choice of near-term hedging strategies under uncertainty, the impacts of learning-by-doing, and the potential importance of *when* and *where* flexibility. To support this scenario research, the multi-gas version has been revised by adjustments in technology and other assumptions. The MERGE code and publications describing its structure and applications can be found at http://www.stanford.edu/group/MERGE/.
- **MiniCAM** is an integrated assessment model (Brenkert et al. 2003) that combines a technologically detailed global energy-economy-agricultural-land-use model with a suite of coupled gas-cycle, climate, and ice-melt models, integrated in the Model for the Assessment of Greenhouse-Gas Induced Climate Change (MAGICC). MiniCAM was developed and is maintained at the Joint Global Change Research Institute, a partnership between the Pacific Northwest National Laboratory and the University of Maryland, while MAGICC was developed and is maintained at NCAR. MiniCAM is solved on a 15-year time step. MiniCAM has been used extensively for energy, climate, and other environmental analyses conducted for organizations that include the U.S. Department of Energy (DOE), the U.S. Environmental Protection Agency, the IPCC, and several major private sector energy companies. Its energy sector is based on a model developed by Edmonds and Reilly (1985). The model is designed to examine long-term, large-scale changes in global and regional energy systems, focusing on the impact of energy technologies. Documentation for MiniCAM can be found in Brenkert et al. (2003).

Because these models were designed to address an overlapping set of climate change issues, they are similar in many respects. All three have social science-based components that capture the socioeconomic and technology interactions underlying the emissions of GHGs, and each incorporates models of physical cycles for GHGs and other radiatively important substances and other aspects of the natural science of global climate. The differences among them lie in the detail and construction of these components and in the ways they are modeled to interact. Each was designed with somewhat different aspects of the climate issue as a main focus. IGSM includes the most detailed representation of the chemistry, physics, and biology of the atmosphere, oceans, and terrestrial biosphere; thus, its EPPA component is designed to provide the emissions detail that these natural science components require. MERGE has its origins in an energy-sector model that was initially designed for energy technology assessment. It was subsequently modified to explore the influence of expectations (and uncertainty regarding expectations) about future climate policy on the economics of current investment and the cost-minimizing allocation of emissions mitigation over time. Its focus requires a forward-looking structure, which in turn employs simplified non-energy components of the economy. MiniCAM is a technology-rich IAM. It features detailed representations of energy technologies, energy systems, and energy markets and their interactions with demographics, the economy, agricultural technologies, markets, land use, and the terrestrial carbon cycle.

Each of these IAMs has unique strengths and areas of special insight. In this research, the simultaneous application of different model structures is useful in revealing different aspects of the task of stabilizing radiative forcing. The differences among the scenarios prepared by the

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[1] It differs from the pure bottom-up approach described in Box 2.1 in that demands for energy are price responsive.

three modeling groups, presented in Chapters 3 and 4, are an indication of the limits of the knowledge about future GHG emissions and the challenges in stabilizing atmospheric conditions. Indeed, differences among the emissions characteristics of the reference scenarios and in the implications of various stabilization targets are likely within the range that would be realized from an uncertainty analysis applied to any one of the three, as indicated by the analysis of the IGSM model by Webster et al. (2003).

Table 2.1 provides a cross-model overview of some of the key characteristics to be compared in the following sections of this chapter. Section 2.2 focuses on social science components, describing similarities and differences and highlighting the assumptions that have the greatest influences on the scenarios. Section 2.3 does the same for the natural science sub-models of each IAM, which in this research make the connection between the emissions of GHGs and the resulting atmospheric conditions.

**Table 2.1. Characteristics of the Models**

| Feature | IGSM (with EPPA Economics Component) | MERGE | MiniCAM |
|---|---|---|---|
| **Regions** | 16 | 9 | 14 |
| **Time Horizon, Time Steps** | 2100, 5-year steps | 2200, 10-year steps | 2095, 15-year steps |
| **Model Structure** | General equilibrium | General equilibrium | Partial equilibrium |
| **Solution** | Recursive dynamic | Inter-temporal optimization | Recursive dynamic |
| **Final Energy Demand Sectors in Each Region** | Households, private transportation, commercial transportation, service sector, agriculture, energy intensive industries, and other industry | A single, non-energy production sector | Buildings, transportation, and industry (including agriculture) |
| **Capital Turnover** | Five vintages of capital with a depreciation rate | A putty clay approach wherein the input-output coefficients for each cohort are optimally adjusted to the future trajectory of prices at the time of investment | Vintages with constant depreciation rate for all electricity-sector capital; capital structure not explicitly modeled in other sectors |
| **Goods in International Trade** | All energy and non-energy goods as well as emissions permits | Energy, energy intensive industry goods, emissions permits, and representative tradable goods | Oil, coal, natural gas, biomass, agricultural goods, and emissions permits |
| **Emissions** | $CO_2$, CH4, $N_2O$, HFCs, PFCs, $SF_6$, CO, $NO_X$, $SO_X$, NMVOCs, BC, OC, $NH_3$ | $CO_2$, $CH_4$, $N_2O$, long-lived F-gases, short-lived F-gases, and $SO_X$ | $CO_2$, $CH_4$, $N_2O$, CO, $NO_X$, $SO_2$, NMVOCs, BC, OC, HFC245fa, HFC134a, HFC125, HFC143a, $SF_6$, $C_2F_6$, and $CF_4$ |
| **Land Use** | Agriculture (crops, livestock, and forests), biomass land use, and land use for wind and/or solar energy | Reduced-form emissions from land-use; no explicit land use sector; assume no net terrestrial emissions of $CO_2$ | Agriculture (crops, pasture, and forests) as well as biomass land use and unmanaged land; the agriculture-land-use module directly determines land-use change emissions and terrestrial carbon stocks. |
| **Population** | Exogenous | Exogenous | Exogenous |

**Table 2.1 Characteristics of the Models, continued**

| Feature | IGSM (with EPPA Economics Component) | MERGE | MiniCAM |
|---|---|---|---|
| **GDP Growth** | Exogenous productivity growth assumptions for labor, energy, and land; exogenous labor force growth determined from population growth; endogenous capital growth through savings and investment | Exogenous productivity growth assumptions for labor and energy; exogenous labor force growth determined from population growth; endogenous capital growth through savings and investment | Exogenous productivity growth assumptions for labor; exogenous labor force growth based on population demographics |
| **Energy Efficiency Change** | Exogenous | Proportional to the rate of GDP growth in each region | Exogenous |
| **Energy Resources** | Oil (including tar sands), shale oil, gas, coal, wind and/or solar, land (biomass), hydro, and nuclear fuel | Conventional oil, unconventional oil (coal-based synthetics, tar sands, and shale oil), gas, coal, wind, solar, biomass, hydro, and nuclear fuel | Conventional oil, unconventional oil (including tar sands and shale oil), gas, coal, wind, solar, biomass (waste and/or residues and crops), hydro, and nuclear fuel (uranium and thorium); includes a full representation of the nuclear fuel cycle |
| **Electricity Technologies** | Conventional fossil (coal, gas, and oil), nuclear, hydro, natural gas combined cycle (NGCC) with and without capture, integrated coal gasification with capture, and wind and/or solar, biomass | Conventional fossil (coal, gas, and oil), nuclear, hydro, new coal and gas with and without CCS, other renewables. | Conventional fossil (coal, gas, and oil) with and without capture; integrated gasification combined cycles (IGCCs) with and without capture; NGCC with and without capture; Gen II, III, and IV reactors and associated fuel cycles; hydro, wind, solar, and biomass (traditional and modern commercial) |
| **Conversion Technologies** | Oil refining, coal gasification, and bio-liquids | Oil refining, coal gasification and liquefaction, bio-liquids, and electrolysis | Oil refining, natural gas processing, natural gas to liquids conversion, coal, and biomass conversion to synthetic liquids and gases; hydrogen production using liquids, natural gas, coal, biomass; and electrolysis, including direct production from wind and solar, and nuclear thermal conversion |
| **Atmosphere-Ocean** | 2-dimensional atmosphere with a 3-dimensional ocean general circulation model, resolved at 20 minute time steps, 4° latitude, 4 surface types, and 12 vertical layers in the atmosphere | Parameterized ocean thermal lag | Global multi-box energy balance model with upwelling-diffusion ocean heat transport |

**Table 2.1 Characteristics of the Models, continued**

| Feature | IGSM (with EPPA Economics Component) | MERGE | MiniCAM |
|---|---|---|---|
| **Carbon Cycle** | Biogeochemical models of terrestrial and ocean processes; depends on climate and/or atmospheric conditions with 35 terrestrial ecosystem types | Convolution ocean carbon cycle model assuming a neutral biosphere | Globally balanced carbon-cycle with separate ocean and terrestrial components, with terrestrial response to land-use changes |
| **Natural Emissions** | $CH_4$, $N_2O$, and weather and/or climate dependent as part of biogeochemical process models | Fixed natural emissions over time | Fixed natural emissions over time |
| **Atmospheric fate of GHGs, pollutants** | Process models of atmospheric chemistry resolved for urban and background conditions | Single box models with fixed decay rates. No consideration of reactive gases | Reduced form models for reactive gases and their interactions |
| **Radiation Code** | Radiation code accounting for all significant GHGs and aerosols | Reduced form, top-of-the-atmosphere forcing | Reduced form and top-of-the-atmosphere forcing; including indirect forcing effects |

## SOCIOECONOMIC AND TECHNOLOGY COMPONENTS

### Equilibrium, Expectations, and Trade

As can be seen in Table 2.1, the three participating models represent economic activity and associated emissions in a similar way; each divides the world economy into several regions, and further divides each region into economic sectors. In all three, the greatest degree of disaggregation is applied to the various components of energy supply and demand.

The models differ, however, in their representations of the equilibrium structure, the role of future expectations, and in the goods and services traded. MERGE and the EPPA component of IGSM are CGE models, which solve for a consistent set of supply-demand and price equilibria for each good and factor of production that is distinguished in the analysis. In the process, CGE models ensure a balance in each period of income and expenditure and of savings and investment for the economy, and they maintain a balance in international trade in goods and emissions permits. MiniCAM is a partial-equilibrium model, solving for supply-demand and price equilibria within linked energy and agricultural markets. Other economic sectors that influence the demand for energy and agricultural products and the costs of factors of production in these sectors are represented through exogenous assumptions.

The models also differ in how expectations about the future affect current decisions. The EPPA component of IGSM and MiniCAM are recursive-dynamic, meaning they are solved one period at a time with economic agents modeled as responding to conditions in that period. This behavior is also referred to as myopic because these agents do not consider expected future market conditions in their decisions. The underlying behavioral assumption is that consumers and producers maximize their individual utilities or profits. In MiniCAM, this process is captured through the use of demand and supply functions that evolve over time as a function of evolving economic activity and regional economic development. In IGSM, explicit representative-agent utility and sector production functions ensure that consumer and producer decisions are consistent with welfare and profit maximization. In both of these models, the patterns of emissions mitigation over time in the scenarios that stabilize radiative forcing are imposed through assumptions intended to capture the features of a strategy that, as explained in Section 2.4, would be cost efficient. MERGE, on the other hand, is an inter-temporal optimization model, meaning that all periods are solved simultaneously such that resources and mitigation effort are allocated optimally over time as well as among sectors. Inter-temporal models of this type are often referred to as forward-looking or perfect foresight models because actors in the economy base current decisions not only on current conditions but on future ones, which are assumed to be known with certainty. Simultaneous solution of all periods ensures that agents' expectations about the future are realized in the model solution. MERGE's forward-looking structure allows it to explicitly solve for cost-minimizing emissions pathways, in contrast to MiniCAM and IGSM, which exogenously prescribe emissions mitigation policies over time.

Although all three models also represent international trade in goods and services and include exchange in emissions permits, they differ in the combinations of goods and services traded. In IGSM, all goods and services represented in the model are traded, with electricity trade limited to geographically contiguous regions to the extent that it occurs in the base data. MiniCAM models international trade in oil, coal, natural gas, agricultural goods, and emission permits. MERGE models trade in oil and natural gas, emissions permits, energy-intensive industrial goods, and a single non-energy good representing all other tradable goods and services.

## Population and Economic Growth

An increase in the overall scale of economic activity is among the most important drivers of GHG emissions. However, economic growth depends, in part, on growth in population, which in all three models is an exogenously determined input. Although economic activity is an output of the models, its level is largely determined by assumptions about labor productivity and labor force growth, which are also model inputs. Policies to reduce emissions below those in the reference scenarios also affect economic activity, which may be measured as changes in gross domestic product (GDP) or in national consumption. (See Chapter 4, which provides a discussion of the interpretation and limitations of GDP and other welfare measures.)

In MiniCAM, labor productivity and growth in the labor force are the main drivers of GDP growth. GDP is calculated as the product of labor force and average labor productivity modified by an energy-service cost feedback elasticity. The labor force and labor productivity are both exogenous inputs to MiniCAM, but were developed for these scenarios from detailed demographic analysis. Starting with the underlying population scenario, the labor force was estimated from age- and gender-specific labor force participation rates applied to the relevant cohorts, then summed and adjusted by a fixed unemployment rate. Trends were explicitly considered, such as the increasing rate of labor force participation by females in the U.S. economy, the aging of the baby boomers, and evolving labor participation rates in older cohorts, reflecting the consequences of changing health and survival rates. Labor force productivity growth rates vary over time and across region to represent these evolving demographics.

In MERGE and the EPPA component of IGSM, the labor force and its productivity, while extremely important, are not the only factors determining GDP. Savings and investment and productivity growth in other factors (e.g., materials, land, labor, and energy) variously contribute as well. IGSM and MERGE use population directly as a measure of the labor force and apply assumptions about labor productivity change that are appropriate for that definition.

## Energy Demand

In all three models, energy demands are represented regionally and driven by regional economic activity. As a region's economic activity increases, its corresponding demand for energy services rises. Energy demand is also affected by assumptions about changes in technology, in the structure of the economy, and in other economic conditions (see Section 2.2.5). Similarly, all the models represent the way demand will respond to changes in price. The formulation of price response is particularly important in the construction of stabilization scenarios because the imposition of a constraint on carbon emissions will require the use of more expensive energy sources with lower emissions and will, therefore, raise the consumer price of all forms of energy.

The demand for energy is derived from demands for other goods and services in all three IAMs. However, the models differ in the way they derive their energy demands. In IGSM each good- or service-producing sector demands energy. The production sector is an input-output structure in which every industry (including the energy sector) supplies its outputs as inputs to intermediate production in other industries and for final consumption. Households have separate demands for automobile fuel and for all other energy services. Each final demand sector can use electricity, liquid fuels (petroleum products or biomass liquids), gas, and coal; fuel for automobiles is limited to liquids. MiniCAM is similar in that each MiniCAM sector demands energy. Energy is demanded by both final consumers and transforming sectors. In MiniCAM, there are three final energy consumption sectors – buildings, industry, and transport – which consume electricity and energy products such as coal, biomass, refined liquid fuels, methane, and hydrogen. In addition, energy is demanded by energy-producing and refining sectors, power generators, and hydrogen producers, whose demands in turn are derived from the demands arising in the final energy consumption sectors. MERGE is similar to IGSM except that its inter-industry transactions are aggregated into a single, non-energy-production sector for each region from which demands for fuels (oil, gas, coal, and bioenergy) and electricity are derived. The power generation sector's demands for energy are derived from the economy's demand for electricity.

## Energy Resources

The future availability of energy resources, particularly of exhaustible fossil fuels, is an important determinant of energy use and emissions, so all three of the participating models provide explicit treatments of the underlying resource base. All three include empirically based estimates of in-ground resources of oil, coal, and natural gas that might ultimately be available, along with a model of the costs of extraction. The levels of detail in the different models are shown in Table 2.1. Each of the models includes both conventional and unconventional sources in its resource base and represents the process of exhaustion of resources by an increasing cost of exploitation. That is, lower-cost resources are utilized first so that the costs of extraction rise as the resources are depleted. The models differ, however, in the way they represent the increasing costs of extraction. MiniCAM divides the resource base for each fossil fuel into discrete grades with increasing costs of extraction, along with an exogenous technological change parameter that lowers extraction costs over time. MERGE has similar differential grades for oil and gas, but assumes that the coal base is more than sufficient to meet potential demand and that exogenous technological improvements in extraction will be minimal. For these reasons, MERGE represents coal as having a constant cost over time irrespective of utilization. IGSM models resource grades with a continuous function, separately identifying conventional oil, shale oil, natural gas, and coal. Fuel-producing sectors are subject to economy-wide technical progress (e.g., increased labor productivity growth), which partly offsets the rise in extraction costs. The models all incorporate tar sands and unconventional gas (e.g., tight gas and coal-seam gas) in the grade structure for oil and natural gas, and each also includes the potential development of shale oil.

The models seek to represent all resources that could be available as technology and economic conditions vary over time and across simulations. Thus, they represent conditions under which currently unused resources could be economically exploited due to advances in technology or higher prices driven by increasing demands. Generally, then, the modeling groups define a resource base that is more expansive than, for example, that of the U.S. Geological Survey, which estimates technological and economic feasibility only at current technology and prices. However, differences exist in the treatments of potentially available resources. MiniCAM includes a detailed representation of the nuclear power sector, including uranium and thorium resources; nuclear fuel fabrication; reactor technology options; and associated fuel-cycle cycles, including waste, storage, and fuel reprocessing. IGSM and MERGE assume that the uranium resources used for nuclear power generation are sufficient to meet likely use and, therefore, do not explicitly model their depletion.

The treatment of wind and solar resources also differs among the models. IGSM represents the penalty for intermittent supply by modeling wind and solar as imperfect substitutes for central station generation, where the elasticity of substitution implies a rising cost as these resources supply a larger share of electricity supply. Land is also an input, and the regional cost of wind and solar energy is based on estimates of regional resource availability and quality. MERGE represents these resources as having a fixed cost, but it applies upper limits on the proportion of these resources in the electricity system, representing limits on the integration of these resources into the grid. MiniCAM represents wind and solar technologies as extracting power from graded, regional, renewable resource bases. Variation in resource availability across diurnal and annual cycles affects market penetration of these technologies. As wind and solar technologies achieve larger fractions of the total power generation system, storage and ancillary power production capacity are required, which in turn affects the cost of power generation and technology choice.

IGSM and MiniCAM model biomass production as competing for agricultural land. Increasing production leads to increasing land rent, representing the scarcity of agricultural land, and thus, to increasing cost of biomass as production expands. MiniCAM also has a separate set of regional supply functions for biomass supplied from waste and residue sources. In these scenarios, MERGE represents biomass as a graded resource. Two grades of biomass are included, with fixed costs for each. The total supply from the first, less-expensive grade is limited, but the second, more-expensive grade is allowed to compete unhindered in the market.

## Technology and Technological Change

Technology is the broad set of processes covering know-how, experience, and equipment used by humans to produce services and transform resources. In the three models participating in this scenario, the relationship between things that are produced and things that are used in the production process are represented mathematically. In the jargon of the models, the relationship between things that are produced and things that are used in the production process is referred to as a production function.

The three modeling groups differed substantially in their representation of technology depending on their overall design objectives. Differences also resulted from data limitations and computational feasibility, which force trade-offs between the inclusion of engineering detail and the representation of the interaction among the segments of a modern economy that determines supply, demand, and prices (see Box 2.1).

All three of the models applied here follow a hybrid approach to the representation of energy technology, involving substantial detail in some areas and more aggregate representations in others, and some of the choices that flow from the distinct design of each can be seen in Table 2.1. They represent energy demand, as described in Section 2.2.3, with the application of an autonomous energy efficiency improvement (AEEI) factor to represent non-price-induced trends in energy use. However, AEEI parameter values are not directly comparable across the models because each has a unique representation of the processes that together explain the multiple forces that have contributed historically to changes in the energy intensity of economic activity. In IGSM and MERGE, the AEEI captures non-price changes (including structural change not accounted for in the models) that can be energy using rather than energy saving. MERGE represents the AEEI as a function of GDP growth in each region. MiniCAM captures shifts among fuels through differing income elasticities, which change over time, and separately represents AEEI efficiency gains.

Other areas shown in Table 2.1 where there are significant differences among the models are in energy conversion – from fossil fuels or renewable sources to electricity and from solid fossil fuels or biomass to liquid fuels or gas. In IGSM, discrete energy technologies are represented as energy supply sectors contained within the input-output structure of the economy. Those sources of fuels and electricity that now dominate supply are represented as production functions with the same basic structure as the other sectors of the economy. Technologies that may play a large role in the future (e.g., power plants with CCS or oil from shale) are introduced as discrete technologies using a production function structure similar to that for existing pro-

## BOX 2.1 Top-Down, Bottom-Up, and Hybrid Modeling

The models used in energy and environmental assessments are sometimes classified as either top-down or bottom-up in structure, a distinction that refers to the way they represent technological options. A top-down model uses an aggregate representation of how producers and consumers can substitute non-energy inputs for energy inputs or relatively energy-intensive goods for less energy-intensive goods. Often, these tradeoffs are represented by aggregate production functions or by utility functions that describe consumers' willingness and technical ability to substitute among goods.

The bottom-up approach begins with explicit technological options, and fuel substitution or changes in efficiency occur as a result of discrete changes from one specific technology to another. The bottom-up approach has the advantage of being able to represent explicitly the combination of outputs, inputs, and emissions of types of capital equipment used to provide consumer services (e.g., a vehicle model or building design) or to perform a particular step in energy supply (e.g., a coal-fired powerplant or wind turbine). However, a limited number of technologies are often included, which may not well represent the full set of possible options that exist in practice. Also, in a pure bottom-up approach, the demands for particular energy services are often characterized as fixed (unresponsive to price), and the prices of inputs such as capital, labor, energy, and materials are exogenous.

On the other hand, the top-down approach explicitly models demand responsiveness and input prices, which usually require the use of continuous functions to model at least some parts of the available technology set. The disadvantage of the latter approach is that production functions of this form will poorly represent switch points from one technology to another – as from one form of electric generation to another or from gasoline to biomass blends as vehicle fuel. In practice, the vast majority of models in use today, including those applied in this scenario, are hybrids in that they include substantial technological detail in some sectors and more aggregate representations in others.

duction sectors and technologies. They are subject to economy-wide productivity improvements (e.g., labor, land, and energy productivity), with the effect on cost depending on the share of each factor in the technology production function. MERGE and MiniCAM also characterize energy-supply technologies in terms of discrete technologies. In the MERGE scenarios in this research, technological improvements are captured by allowing for the introduction of more advanced technologies in future periods. In the MiniCAM scenarios, the cost and performance of technologies are assumed to improve over time, and new technologies become available in the future. Similar differences among the models hold for other conversion technologies, such as coal gasification, coal liquefaction, or liquids from biomass.

The entry into the market of new sources and their levels of production by region are determined endogenously in all three models and depend on the relative costs of supply. It should be emphasized that the versions of the models used in this research do not explicitly represent the processes of technological change, for example, public and private R&D, spillovers from innovation in other economic sectors, and learning-by-doing. A number of recent efforts have been made to incorporate such processes and their effects as an endogenous component of modeling exercises. In most cases, these studies have not been applied to models of the complexity needed to meet the requirements of this scenario product.

Because of the differences in structure among these models, there is no simple technology-by-technology comparison of performance and cost across particular sources of supply or technological options. This situation exists for a variety of reasons. First, cost is an output of the three models and not an input. In the three models here technologies are defined in many cases not in terms of some exogenously specified cost, but rather as a function of inputs whose prices change across simulations and over time. The three models differ in many regards. Each model defines the scope of a technology differently. Sectoral definitions, technology definitions, and data sources all vary across the three models. For example, one model has a service sector while another has a buildings sector. There is then, no common definition for technologies, technology descriptors and hence for a set of comparable costs. The detailed scenario documentation for each of the three modeling groups provides more information about the technology assumptions employed by three modeling groups. These are documented in Paltsev et al. (2005) for IGSM and in Clarke et al. (2007) for MiniCAM. Assumptions for MERGE are included in the version of the model posted at http://www.stanford.edu/group/MERGE.

The influence of differing technology specifications and assumptions is evident in the scenarios discussed in Chapters 3 and 4. For example, in the absence of efforts to control GHG emissions, motor fuel is drawn ever more heavily from high-emitting sources. Oil from shale comes in under the resource and technology assumptions used in the IGSM scenarios, whereas liquids from coal figure prominently in the MERGE scenarios, and the MiniCAM scenarios include an intermediate mix of both. Furthermore, because each model assumes market mechanisms operate efficiently, the marginal cost of reducing GHG emissions – that is the cost of reducing the last tonne of GHG – is equal to the price of carbon in every technology employed in every sector and in every country of the world. When stabilization conditions are imposed, CCS takes on a key role in all the scenarios over the time period considered in this research. Nuclear power contributes heavily in MERGE and in MiniCAM scenarios, whereas the potential role of this technology is overridden in the IGSM scenarios by an assumption of non-climate restraints on expansion due to concerns over issues such as safety, waste, and proliferation. Finally, although differences in emissions in the reference scenario contribute to variations in the difficulty of achieving stabilization, alternative assumptions about technological improvements also play a prominent role.

## Land Use and Land-Use Change

The models used in this research were developed originally with a focus on energy and fossil carbon emissions. The integration of the terrestrial biosphere, including human activity, into the climate system is less highly developed. Each model represents the global carbon cycle, including exchanges among the atmosphere, natural vegetation, and soils; the effects of human land use and responses to carbon policy; and feedbacks to the global climate. No model represents all of these possible responses and interactions, and the level of detail varies substantially among the models. For example, the models differ in their handling of natural vegetation and soils and in their responses to change $CO_2$ concentrations and climate. Furthermore, land-use practices (e.g., low- or no-till agriculture and biomass production) and changes in land use (e.g., afforestation, reforestation, or deforestation) that influence GHG emissions and the sequestration of carbon in terrestrial systems are handled at different levels of detail. Indeed, improved two-way linking of global economic and climate analysis with models of physical land use (land use responding to climate and economic pressures and climate responding to changes in the terrestrial biosphere) is the subject of ongoing research in these modeling groups.

In IGSM, land is an input to agriculture, biomass production, and wind and/or solar energy production. Agriculture is a single sector that aggregates crops, livestock, and forestry. Biomass energy production is modeled as a separate sector, which competes with agriculture for land. Markets for agricultural goods and biomass energy are international, and demand for these products determines the price of land in each region and its allocation among uses. In other sectors, returns to capital include returns to land, but the land component is not explicitly identified. Anthropogenic emissions of GHGs (importantly, $CH_4$ and $N_2O$) are estimated within IGSM as functions of agricultural activity and assumed levels of deforestation. The response of terrestrial vegetation and soils to climate change and $CO_2$ increase is captured in the Earth system component of the model, which provides a detailed treatment of biogeochemical and land-surface properties of terrestrial systems. However, the biogeography of natural ecosystems and human uses remains unchanged over the simulation period, with the area of cropland fixed to the pattern of the early 1990s. Balance in the carbon cycle between ocean uptake, land-use and land-use change, and anthropogenic emissions is achieved in

IGSM with an adjustment factor to ensure that the recent trend in atmospheric $CO_2$ increase is replicated. This adjustment factor is best interpreted as what carbon uptake due to forest regrowth must have been, given the representation of terrestrial and ocean systems in IGSM. The need for such an adjustment factor reflects the continuing scientific uncertainty in the carbon cycle. In other words, with fossil emissions and concentrations relatively well known, the total uptake is known but the partitioning of the uptake between terrestrial and ocean systems is uncertain (Sabine et al. 2004). IGSM does not simulate carbon price-induced changes in carbon sequestration (e.g., reforestation and tillage), and change among land-use types in the EPPA component of IGSM is not fed to the terrestrial biosphere component of the model.

The MERGE modeling group assumed a neutral terrestrial biosphere across all scenarios. That is, it is assumed that the net $CO_2$ exchange with the atmosphere by natural ecosystems and managed systems – the latter including agriculture, deforestation, afforestation, reforestation, and other land-use change – sums to zero.

MiniCAM includes a model that allocates the land area in a region among various components of human use and unmanaged land – with changes in allocation over time in relation to income, technology, and prices – and estimates the $CO_2$ emissions (or sinks) that result. Land conditions and associated emissions are parameterized for a set of regional sub-aggregates. The supply of primary agricultural production (four food crop types, pasture, wood, and commercial biomass) is simulated regionally with competition for a finite land resource based on the average profit rate for each good potentially produced in a region. In stabilization scenarios, the value of carbon stored in the land is added to this profit, based on the average carbon content of different land uses in each region. This allows carbon mitigation policies to explicitly extend into land and agricultural markets. The model is solved by clearing a global market for primary agricultural goods and regional markets for pasture. The biomass market is cleared with demand for biomass from the energy component of the model. Exogenous assumptions are made for the rate of intrinsic increase in agricultural productivity, although net productivity can decrease in the case of expansion of agricultural lands into less productive areas (Sands and Leimbach 2003). Unmanaged land can be converted to agro-forestry, which in general leads to net $CO_2$ emissions from tropical regions in the early decades. Emissions of non-$CO_2$ GHGs are tied to relevant drivers, for example, with $CH_4$ from ruminant animals related to beef production. MiniCAM thus treats the effects on carbon emissions of gross changes in land use (e.g., from forests to biomass production) using an average emission factor for such conversion. The pricing of carbon stocks in the model provides a counterbalance to increasing demand for biomass crops in stabilization scenarios.

## Emissions of $CO_2$ and Non-$CO_2$ Greenhouse Gases

In all three models, the main source of $CO_2$ emissions is fossil fuel combustion, which is computed on the basis of the carbon content of each of the underlying resources: oil, natural gas, and coal. Special adjustments are made to account for emissions associated with the additional processing required to convert coal, tar sands, and shale sources into products equivalent to those from conventional oil. Other industrial $CO_2$ emissions also are included, primarily from cement production.

As required for this research, all three models include representations of emissions and abatement of $CH_4$, $N_2O$, HFCs, PFCs, and $SF_6$ (plus aerosols and other substances not considered in this scenario). The models use somewhat different approaches to represent abatement of non-$CO_2$ GHGs. IGSM includes the emissions and abatement possibilities directly in the production functions of the sectors that are responsible for emissions of the different gases. Abatement possibilities are represented by substitution elasticities in a nested structure that encompasses GHG emissions and other inputs, benchmarked to reflect bottom-up studies of abatement potential. This construction is parallel to the representation of fossil fuels in production functions, where abatement potential is similarly represented by the substitution elasticity between fossil fuels and other inputs, with the specific set of substitutions governed by the nest structure. Abatement opportunities vary by sector and region.

In MERGE, $CH_4$ emissions from natural gas use are tied directly to the level of natural gas consumption, with the emissions rate decreasing over time to represent reduced leakage during the transportation process. Non-energy sources of $CH_4$, $N_2O$, HFCs, PFCs, and $SF_6$ are based largely on the guidelines provided by the EMF Study No. 21 on Multi-Gas Mitigation and Climate Change (de la Chesnaye and Weyant 2006). The EMF developed baseline projections from 2000 through 2020. For all gases but $N_2O$ and $CO_2$, the baseline for beyond 2020 was derived by extrapolation of these estimates. Abatement cost functions – the relationship between levels of emissions reductions and the costs of these reductions – for these two gases are also based on EMF 21, which provided estimates of the abatement potential for each gas in each of 11 cost categories in 2010. These abatement cost curves are directly incorporated in the model and extrapolated after 2010 following the baseline. There is also an allowance for technical advances in abatement over time.

MiniCAM calculates emissions of $CH_4$, $N_2O$, and seven categories of industrial sources for HFCs, PFCs, and $SF_6$. Emissions are determined for over 30 sectors, including fossil fuel production, transformation, and combustion; industrial processes; land use and land-use change; and urban emissions. For details, see Smith (2005) and Smith and Wigley (2006). Emissions are proportional to driving factors appropriate for each sector, with emissions factors in many sectors decreasing over time according to an income-driven logistic formulation. Marginal abatement cost (MAC) curves from the EMF-21 study are applied, including shifts in the curves for $CH_4$ due to changes in natural gas prices. Any below-zero reductions in MAC curves are assumed to apply in the reference scenario.

## EARTH SYSTEMS COMPONENTS

The Earth system components of the models represent the response of the atmosphere, ocean, and terrestrial biosphere to emissions and increasing concentrations of GHGs and other substances. Representation of these processes, including the carbon cycle (Box 2.2), is necessary to determine emissions paths consistent with stabilization because these systems determine how long each of these substances remains in the atmosphere and how they interact in altering the Earth's radiation balance. Each model includes such physical-chemical-biological components, but incorporates different levels of detail. The most elaborated Earth system components are found in IGSM (Sokolov et al. 2005), which falls in a class of models referred to as Earth System Models of Intermediate Complexity (Claussen et al. 2002). These are models that fall between the full three-dimensional atmosphere-ocean general circulation models (AOGCMs) and energy balance models with a box model of the carbon cycle. The Earth system components of MERGE and MiniCAM fall in the class of energy balance-carbon cycle box models. Table 2.1 shows how each of the models treat different components of the Earth systems.

IGSM has explicit spatial detail, resolving the atmosphere into multiple layers and by latitude, and it includes a terrestrial vegetation model with multiple vegetation types that are also spatially resolved. A version of IGSM with a full three-dimensional ocean model was used for this scenario, and it includes temperature-dependent uptake of carbon. IGSM models atmospheric chemistry, resolved separately for urban (i.e., heavily polluted) and background conditions. Processes that move carbon into or out of the ocean and vegetation are modeled explicitly. IGSM also models natural emissions of $CH_4$ and $N_2O$, which are weather and/or climate-dependent. The model includes a radiation code that computes the net effect of atmospheric concentrations of the GHGs studied in this research. Also included in the global forcing is the effect of changing ozone and aerosol levels, which result from emissions of $CH_4$ and non-GHGs, such as $NO_X$ and volatile organic hydrocarbons; $SO_X$; black carbon; and organic carbon from energy, industrial, agricultural, and natural sources.

The carbon cycle in MERGE relates emissions to concentrations using a convolution ocean carbon-cycle model and assuming a neutral biosphere (i.e., no net $CO_2$ exchange). It is a reduced-form carbon cycle model developed by Maier-Reimer and Hasselmann (1987). Carbon emissions are divided into five classes, each with different atmospheric lifetimes. The be-

## BOX 2.2 The Carbon Cycle

Although an approximate atmospheric lifetime is sometimes calculated for $CO_2$, the term is potentially misleading because it implies that $CO_2$ put into the atmosphere by human activity always declines over time by some stable removal process. In fact, the calculated concentration of $CO_2$ is not related to any mechanism of destruction, or even to the length of time an individual molecule spends in the atmosphere, because $CO_2$ is constantly exchanged between the atmosphere and the surface layer of the ocean and with vegetation. Instead, it is more appropriate to think about how the quantity of carbon that the Earth contains is partitioned between stocks of in-ground fossil resources, the atmosphere (mainly as $CO_2$), surface vegetation and soils, and the surface and deep layers of the ocean. When stored carbon is released into the atmosphere, either from fossil or terrestrial sources, atmospheric concentrations of $CO_2$ increase, leading to disequilibrium with the ocean, and more carbon is taken up than is cycled back. For land processes, vegetation growth may be enhanced by increases in atmospheric $CO_2$, and this change could augment the stock of carbon in vegetation and soils. As a result of the ocean and terrestrial uptake, only about half of the carbon currently emitted remains in the atmosphere. Over millennial time scales, oceans would continue to remove carbon until a large fraction, presently about 80%, would ultimately be removed to the oceans, leaving about 20% as a permanent increase in the atmospheric $CO_2$ concentration. But this large removal only occurs because current levels of emissions lead to substantial disequilibrium between atmosphere and ocean. Lower emissions would lead to less uptake, as atmospheric concentrations come into balance with the ocean and interact with the terrestrial system. Rising temperatures themselves will reduce uptake by the ocean, and will affect terrestrial vegetation uptake, processes that the models in this scenario variously represent.

An important policy implication of these carbon-cycle processes as they affect stabilization scenarios is that stabilization of emissions near the present level will not lead to stabilization of atmospheric concentrations. $CO_2$ concentrations were increasing in the 1990s at just over 3 ppmv per year, an annual increase of 0.8%. Thus, even if societies were able to stabilize emissions at current levels, atmospheric concentrations of $CO_2$ would continue to rise. As long as emissions exceed the rate of uptake, even very stringent abatement will only slow the rate of increase.

havior of the model compares favorably with atmospheric concentrations provided in the IPCC's Third Assessment Report (TAR) (IPCC 2001) when the same SRES scenarios of emissions are simulated in the model (Nakicenovic et al. 2000). MERGE models the radiative effects of GHGs using relationships consistent with summaries by the IPCC, and applies the median aerosol forcing from Wigley and Raper (2001). The aggregate effect is obtained by summing the radiative forcing effect of each gas.

MERGE's physical Earth system component is embedded in the inter-temporal optimization framework, thus allowing solution of an optimal allocation of resources through time, accounting for damages related to climate change, or optimizing the allocation of resources with regard to other constraints such as concentrations, temperature, or radiative forcing. In this research, the second of these capabilities is applied, with a constraint on radiative forcing (see Chapter 4). In contrast, the IGSM and MiniCAM Earth system models are driven by emissions as simulated by the economic components. In that regard, they are simulations rather than optimization models.

MiniCAM uses the MAGICC model (Wigley and Raper 2001, 2002) as its biophysical component. MAGICC is an energy-balance climate model that simulates the energy inputs and outputs of key components of the climate system (sun, atmosphere, land surface, and ocean) with parameterizations of dynamic processes such as ocean circulations. It operates by taking anthropogenic emissions from the other MiniCAM components, converting these to global average concentrations (for gaseous emissions), then determining anthropogenic radiative forcing relative to preindustrial conditions, and finally computing global mean temperature changes. The carbon cycle is modeled with both terrestrial and ocean components. The terrestrial component includes $CO_2$ fertilization and temperature feedbacks; the ocean component is a modified version of the Maier-Reimer and Hasselmann (1987) model that also includes temperature effects on the terrestrial biosphere. Net land-use change emissions from the MiniCAM's land-use change component are fed into MAGICC so that the global carbon cycle is consistent with the amount of natural vegetation. Reactive gases and their interactions are modeled on a global-mean basis using equations derived from results of global atmospheric chemistry models (Wigley et al. 2002).

In MiniCAM, global mean radiative forcing for $CO_2$, $CH_4$, and $N_2O$ are determined from GHG concentrations using analytic approximations. Radiative forcing for other GHGs are taken to be proportional to concentrations. Radiative forcing for aerosols (for sulfur dioxide and for black and organic carbon) are taken to be proportional to emissions. Indirect forcing effects, such as the effect of $CH_4$ on stratospheric water vapor, are also included. Given radiative forcing, global mean temperature changes are determined by a multiple box model with an upwelling-diffusion ocean component. The climate sensitivity is specified as an exogenous parameter. MAGICC's ability to reproduce the global mean temperature change results of AOGCMs has been demonstrated (Cubasch et al. 2001, Raper and Gregory 2001).

Although aerosols and ozone are not included in the computation of the radiative forcing targets that are the focus of these scenarios, they are nonetheless included in these scenarios as noted above. That is, the radiative forcing stabilization levels identified in Table 1.2 and the radiative forcing levels reported in subsequent chapters account for only that part of radiative forcing due to those GHGs covered by the target. The models can simulate total radiative forcing including additional positive forcing from ozone and dark aerosols and negative forcing from sulfate aerosols. As shown by Prinn et al. (In Press), even for very large changes in emissions related to these substances, the temperature effect is small, in large part because aerosols and ozone have offsetting cooling and warming effects. To the extent temperature is affected by these substances, however, they have a small, indirect influence on the scenarios because trace gas cycles are climate-dependent. For example, climate affects vegetation and ocean temperature and, thus, carbon uptake, and natural emissions of $CH_4$ and $N_2O$, and the lifetime of $CH_4$ also depends on climate. Because the net effect of these substances on temperature is small, the feedback effect on trace gas cycles also is very small. However, to the extent these feedbacks are represented in the models as discussed above, they are included in the calculation of required emissions reduction because the temperature paths, while not reported here, are simulated in the models and affect the $CO_2$ and non-$CO_2$ GHG concentrations. By the same token, the gases included under the Montreal Protocol, which are being phased out, are nonetheless included in these models and exert some influence on temperature.

Note that although the models used in this research have capabilities to evaluate various climate change effects, with few exceptions, they do not include the consequences of such feedback effects as: temperature on home heating and cooling requirements; local climate change on agricultural productivity; $CO_2$ fertilization on agricultural productivity (though a $CO_2$ fertilization effect is included in the terrestrial carbon cycle models employed by IGSM and MiniCAM); climate on water availability for applications ranging from crop growing to power plant cooling. Such improvements are left to future research.