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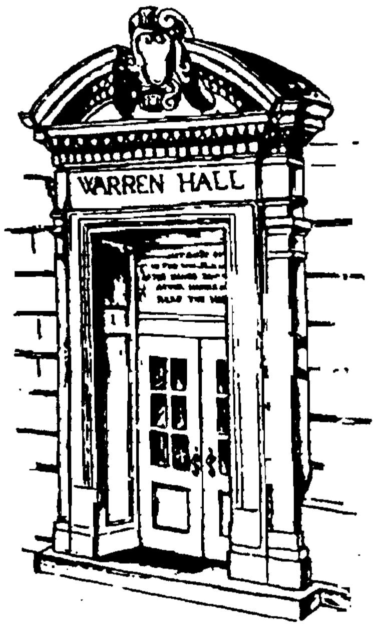

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Penn State - Cornell Integrated Assessment Model

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ABSTRACT

In the past decade dynamic geoeconomic climate modelling has been successful in integrating basic relations in macroeconomic growth and climatology. Now physical scientists and economists at The Penn State University and Cornell University propose to link transient annual climate modelling with the greenhouse gas emissions resulting from a macroeconomic-energy model. In climatological terminology, this is a 3-dimensional General Circulation Model with detailed time and geographic data at the 4.5 degree latitude by 7.5 degree longitude level. The integrated model analysis may proceed up to periods with 10-15 times today's CO_2 equivalent concentration level.

Feedback effects include space heating and cooling energy demand, and natural ecosystem relationships such as CO_2 fertilization and terrestrial CH_4 release.

In the macroeconomic submodel, an augmented Hotelling analysis incorporates long-term depletion with short-term rising market equilibrium values which reflect growing populations and income. Energy demand is explicitly represented by demand functions, as is the possibility of renewable energy, conservation, or nuclear substitution for fossil fuel, as well as the substitution of coal-based energy services for those now provided by petroleum and natural gas.

On a detailed regionally disaggregated level, climate change interactions would be studied for agriculture, morbidity and mortality, sea level rise, and income levels.

The Framework Convention on Climate Change charges policy makers to find stable greenhouse gas concentrations "at a level that would prevent dangerous anthropogenic interference with the climate system." The Penn State-Cornell Integrated Assessment Model would assist in defining those concentration levels, and the national and international policy pathways such as marketable permits or taxation.

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1. Introduction

Integrated assessment models of climate change are rapidly improving, particularly in relation to the state-of-the-art less than a decade ago. However, a gap currently exists between the growing knowledge base of climate change impacts and the impact parameterizations included in most integrated assessment models (Callaway, 1995). Furthermore, several of the other components intrinsic to most current integrated assessment models do not reflect the level of sophistication that has been developed outside the auspices of integrated modeling efforts (Weyant *et al.*, 1996).

For the past several years physical scientists and economists at The Pennsylvania State University and Cornell University have been involved in research programs focused on several separate facets of the climate change issue. We plan to improve upon several weaknesses in the existing state-of-the-art of 'end-to-end' integrated assessment modeling. This document describes the structure and innovative components of the proposed Penn State - Cornell Integrated Assessment (PCIA) model. Highlighted below are a few of the principal innovations of the PCIA model:

- Climate change impact analysis will be driven by output from transient runs of a three-dimensional general circulation model (GCM) of the atmosphere. This type of interactive coupling is a new and important step in the integrated assessment of climate change.
- Spatially detailed impact analyses will include explicit assessment of effects and adaptations associated with agriculture, natural ecosystems, space heating and cooling energy demand, sea level rise, and morbidity and mortality. Multiple feedbacks will be incorporated between the impacted sectors and the macroeconomy as a whole. The

dependence of impacts on the rate of climate change will be explicitly modeled, taking into account the time constants of the affected capital. Explicit climate change impacts will be estimated for CO_2-equivalent concentrations up to 8 times the present level.

- Usage of multiple fuel types will be endogenously determined through an augmented Hotelling form, allowing petroleum and gas use to grow in the near-term while ultimately declining. Alternatively, the augmented Hotelling analysis with rising population and income can be used in a framework which specifies substitutes for conventional petroleum and coal (e.g. nuclear, advanced fossil fuel, and solar technologies).
- Energy demand functions will be provided with own- and cross-price elasticities.
- An explicit, regionally disaggregated policy analysis framework will be created in which the economic efficiency and international and intergenerational equity implications of various emissions reduction mechanisms (e.g. taxation, tradeable permits, and quotas) can be explored.
- Changes in regions' economic welfare, as measured by producer and consumer surplus, can be determined for climate change impacts, and policy.
- Greenhouse gas (GHG) and aerosol inputs to the atmosphere will be determined as a function of regional economic activity and natural ecosystem changes. The atmospheric CO_2 concentration will be computed using a box-diffusion model of the oceans and a spatially disaggregated model of the terrestrial carbon cycle.
- The model will have the ability to determine optimal GHG target concentrations as well as the optimal temporal path for approaching the targets. Fuel specific, optimal emission rates will be determined.

- Detailed assessments of specified policy scenarios in addition to reduced-form, dynamic optimization assessments will be possible through a self-consistent, two-tiered model structure.

Thus, the PCIA model offers several major contributions to the end-to-end integrated assessment arena; in effect, it brings together many state-of-the-art components of climate change research. A major purpose of this modeling effort is to address fundamental questions of climate change policy, such as:

(1) What is the optimal, long-term 'target' concentration of greenhouse gases?

(2) Given a long-term 'target', what is the optimal time path that we should follow to reach it?

The first question is one that is at the center of the United Nations' Framework Convention on Climate Change. The convention's summary document, now signed by over 160 countries, states as the final aim of international climate change policy that greenhouse gas concentrations should be stabilized "at a level that would prevent dangerous anthropogenic interference with the climate system." Working Group I of the Intergovernmental Panel on Climate Change (IPCC) has explored some of the policy implications associated with stabilizing the atmospheric CO_2 concentration at a number of different levels (Schimel *et al.*, 1996).

While there is keen interest in the international research community for stabilizing GHG concentrations, very little has been published with regards to quantitatively assessing optimal target GHG concentrations. Using *ad hoc* GHG concentration targets, several previous studies have examined some of the policy and environmental options and implications that will lead to given target levels (e.g. Crosson, 1989; Manne and Richels, 1992 and 1993; Tahvonenen *et al.*, 1994; Schimel *et al.*, 1995; and Wigley *et al.*, 1996). The proposed PCIA model will be uniquely capable of quantitatively addressing the question of what the target GHG concentrations should be. In brief, this will be accomplished by estimating the long-term marginal costs of reducing GHG emissions and the long-term marginal economic 'benefits' (i.e. averted damages) associated with a variety of stabilized GHG concentrations. In this context, the optimal GHG target concentration is the GHG concentration that produces an intersection of the long-term marginal cost and benefit functions (Figure 1). By examining the response of the cost and benefit functions to a variety of underlying assumptions we will quantify a probable range for the optimal target. In effect what this represents is treating the long-term GHG concentration as a control variable. This is in contrast to previous optimization studies that have only treated the emissions of GHGs as a control variable, with concentration levels implicit at best (e.g. Nordhaus, 1992 and 1994; Nordhaus and Yang, 1996; Peck and Teisberg, 1995).

Once estimates of target GHG levels have been made, the next question to be answered is what temporal trajectory should we follow to reach those targets. The PCIA model is designed to explore a variety of regionally delineated policy options that will achieve the designated target within a cost-benefit framework that is consistent with the quantitative estimation of the optimal target level.

While the standard PCIA model will include a relatively high level of complexity, particularly with regards to the environmental and economic impacts, a reduced-form version of the PCIA model will be constructed that will facilitate the computation of dynamically optimized policy trajectories. Thus, one of the original contributions of the PCIA model is its two-tiered model hierarchy that will allow self-consistent analyses of both detailed specified scenarios in addition to dynamic optimization. See Appendix A for a discussion of why a reduced-form dynamically optimizing model is imperative

The detailed scenarios analysis (DSA) model tier will incorporate regionally disaggregated modules reflecting the state-of-the-art in greenhouse gas chemistry, environmental change, economic impact assessment, energy usage, and climate change policy implementation. The temporal evolution of GHG abatement, climate change adaptation, and capital investment policies will be exogenously specified in the DSA model tier, whereas these parameters will be determined in the optimization model through the maximization of a user-specified utility function. The DSA model tier will consist of five modules that are connected through numerous feedbacks, whereas the dynamic optimization model tier will include highly parameterized versions of these modules. We have previously developed a methodology that will translate the functionality of the DSA model tier into the reduced-form dynamic optimization model tier (Schultz and Kasting, 1996).

An innovative aspect of the PCIA model will be the utilization of general circulation model (GCM) output of climate change to drive the Impact Assessment Module. The Impact Assessment Module will explicitly treat the following variables on a spatially disaggregated basis: space heating and cooling energy usage, morbidity and mortality, natural ecosystems, coastal impacts, and agriculture. As a result of the detailed individual treatment of the affected sectors in the Impact Assessment Module, we will be able to estimate global climate change damages on a national (or finer) scale as a function of the rate, magnitude, and timing of environmental change.

The Macroeconomic Module will calculate broad economic variables for 15 regions comprising the world. One of the novel features of the Macroeconomic Module will be that energy prices will be determined based upon a detailed treatment of specific fuel types, their depletion, and own- and cross-price elasticities, instead of through exogenous specification. Furthermore, GHG emission abatement, specified (or predicted in the case of the optimizing model version) in the Macroeconomic Module, will be linked to specific energy types.

The Policy Analysis Module will facilitate the exploration of a variety of regional and global policy options pertaining to climate change. Among these options are alternatives in energy pricing (competitive and non-competitive), energy taxation, and marketable permit programs. In addition, this module will allow a variety of issues concerning international and intergenerational equity and efficiency to be examined through, for instance, alternative assumptions regarding burden sharing, time preference, and the definition of utility.

II. Components of the Penn State - Cornell Integrated Assessment Model

One of the underlying goals of this modeling effort is to strive to fill the gap that currently exists between the growing knowledge base of climate change impacts and the impact parameterizations included in integrated assessment models (Callaway, 1995; Fankhauser and Tol, 1996). The five linked modules of PCIA model, described below, reflect many of the state-of-the-art elements produced by intra-disciplinary research outside of the auspices of end-to-end integrated modeling efforts. Figure 2 illustrates the key components of the DSA model tier, which includes the following Modules: Macroeconomics, GHG and Aerosol Concentration, Climate Change, Impact Assessment, and Policy Analysis.

II.1 Macroeconomic Module

II.1.1 Global Macroeconomics

The purpose of this module is to determine the broad economic and energy aggregates that will initiate the inputs into the aerosol, climate change, impact, and policy modules. While following the logic of a conventional optimal economic growth framework, the module incorporates important behavioral features of energy markets. In this respect, it builds upon and advances the work of Nordhaus (1992 and 1994), Manne and Richels (1992), Peck and Teisberg (1992 and 1995), Manne *et al.* (1995), and Chapman *et al.* (1995) which are reviewed in table B.1 of Appendix B. The distinguishing feature of the present framework is the synergistic complementarity between the Hotelling and the Ramsey type models. Compare this with table B.2 in Appendix B where none of the models reviewed explicitly model oil production as a dynamic optimization problem for a non-renewable resource. Figures 3 and 4 are a schematic presentation of the work by Nordhaus and the proposed model, respectively.

The model is designed to maximize the present value of global welfare by choosing optimally in each period the level of investment in tangible capital, I_t, and the level of a composite energy commodity, E_t. Thus,

$$(1) \quad \underset{[I_t, E_t]}{Max} \quad \sum_{t=0}^{T} \frac{U(\cdot)}{(1+\rho)^t}$$

where $U(\bullet)$ is the utility function representing global welfare, and ρ is the rate of time preference. The formulation of the utility function is discussed further in the context of the Policy Analysis Module in section II.5.

World economic product, Q_t, is produced as a nested, constant elasticity of substitution production function in capital, K_t, labour, L_t, the composite energy commodity, E_t, and technology, A. This can be formulated as:

(2) $Q_t = A_1[\delta N_t^{\rho} + (1-\delta)E_t^{\rho}]^{1/\rho}$

(3) $N_t = A_2[K_t^{\alpha} L_t^{(1-\alpha)}]$

(4) $E_t = A_3[AEEI_t qcoal_t^{\beta} qoil_t^{\gamma} qngas_t^{\theta} .....]$

(5) $0 \leq \delta \leq 1, \quad 0 \leq \alpha \leq 1, \quad \beta,\gamma,\theta \geq 0, \quad 0 \neq \rho < 1$

where N_t, is the composite capital and labour input, E_t, is the composite energy input, A_1, A_2, and A_3 are scale factors, a, β, γ, θ, and δ are parameters, and $AEEI_t$ represents autonomous energy efficiency improvements. Labour and technology inputs are determined exogenously.

World outputs of oil and natural gas, q_t^m *(m = oil, natural gas)* are determined separately through augmented, optimal control, Hotelling models for nonrenewable energy markets. Both fuels have a finite stock of remaining resources, S^i, and face steadily rising extraction costs, C_t^i. In addition, the demand curves, $P_t^m(\bullet)$, shift over time in response to a growing population, L_t, and rising per capita incomes, Y_t, and also the price of substitute fuels, P_t^{subs}. In both cases, the backstop cost, P_t^{back}, sets the upper bound on their respective prices. These producers maximize the net present value of profits, given these constraints.[1] That is, maximize NPV w.r.t. $[q_t^m, \; T^m]$, where

(6) $$NPV^m = \sum_{t=0}^{T} \frac{P_t^m(q_t^m, L_t, Y_t, P_t^{subs}) - C^m(t)]q_t(\cdot)}{(1+r)^t}$$

[1] Chapman (1993) developed the augmented Hotelling model to take cognizance of the temporally shifting demand for oil, and Khanna and Chapman (1996b) have applied it to the integrated assessment framework developed by Nordhaus (1994). Some of the results obtained by Khanna and Chapman (1996b) are shown in figures 5 and 6.

such that

$$(7) \quad \sum_{t=0}^{T} q_t^m \leq S^m$$

$$(8) \quad P_t^m \leq P_t^{back}$$

$$(9) \quad P_t^m, q_t^m, P_t^m - q_t^m \geq 0$$

Note that the parameter *r* in equation (6) refers to the rate of return on capital, which is determined from the optimal growth model. Conventional oil and gas resources are supplemented by demand for new energy technologies as their prices rise to the cost of the corresponding backstop, P^{back}.

There are sufficient coal resources to meet any foreseeable demand for many centuries. Hence, it is assumed that the supply of coal will adjust to meet the optimally determined demand, $qcoal_t$, in each period.[2] The same is assumed to hold for the backstop energy sources. These per capita demands are constant elasticity of substitution functions in per capita income, own price, and the price of other fuels.

The different energy sources are each substitutable for one another to varying degrees. This feature is captured in the formulation of the composite energy commodity, E_t, which combines the different energy types to form a single entity that is an input in the aggregate production function (see equation 4).

The level of gross world economic product and the fuel mix together determine global

[2] Long-term future analysis may alter this assumption.

energy costs, EC_t. Disposable world output, DQ_t, calculated as gross world product less the sum of energy costs and climate change related damage costs, Dam_t, is apportioned between aggregate consumption, C_t, investment in capital, I_t, and climate change mitigation costs, Mit_t. Thus, the following pair of identities is assumed to hold:

(10) $$DQ_t \equiv Q_t - EC_t - Dam_t \equiv C_t + I_t + Mit_t$$

The capital balance equation, equation (6), captures the dynamics of the economic system. The capital stock in any period, K_t, is determined by the investment level, and the depreciated level of the previous period's capital stock:

(11) $$K_t = I_t + (1-\delta)K_{t-1}$$

The initial stock of capital, K_0, is specified exogenously.

Energy related emissions of CO_2, CO, CH_4, SO_2, and other pollutants are determined via coefficients, v, that translate energy units to emission units of the different pollutants. The total emissions of a single pollutant, X (e.g. CO_2), are represented by:

(12) $$X_t^j = \sum_{f=1}^{F} v^{jf} * FUEL_t^f$$

where j = set of all pollutants

f = set of all fossil fuels

X_t^j = total emissions of pollutant j at time t

$FUEL_t^f$ = consumption of fossil fuel of type f at time t

In the current formulation of the model, regional pollution and climate change are the by-products of the drive for increased consumption.

The long-term marginal emissions reduction cost function that will be used in estimating the optimal GHG concentration target will depend not only on the GHG concentration but also on time (figure 7). The reason that time enters into the function is because the varying lifetime of CO_2 emissions (Kasting and Schultz, 1996) precludes a one-to-one correspondence between an emission rate and an equilibrium atmospheric CO_2 concentration (Wigley *et al.*, 1996). In other words, the stabilization of the atmospheric CO_2 concentration requires an emission rate that declines with time. A range of long-term marginal cost surfaces will be computed using probable ranges of parameter values within the Macroeconomic Module. These cost surfaces, in combination with a marginal long-term benefit curve (derived in the Climate Change and Impact Assessment Modules), will allow a probable range of optimal GHG target concentrations to be computed.

Table 1, overleaf, summarizes the model in terms of its input and output variables.

Table 1: Global Macroeconomic Variables

Global input variables	Global output variables
Population	Gross & per capita consumption
Initial capital stock	Investment flow & capital stock
Technology development & AEEI	Energy costs & taxes
Heating & cooling degree day change	Coal, oil, gas, & other energy use
Remaining oil & gas resources	Composite energy

Supply cost & and carbon content for different energy sources	Energy related emissions of CO_2, SO_2, CO, CH_4, & other pollutants
Rate of time preference	Productivity impacts of climate change
Optimization goal	Rate of return on capital
Market form & pricing rule	
Policy for taxation, permits	
Climate change damage assessment	

II.1.2 Regional Macroeconomics

The next step is to estimate values at the appropriate regional level in an internally consistent manner. This requires the following equation system be solved for each period, *t*.

$$(13)\quad Q_t^i = A_1^i[\delta^i(NE_t^i)^\rho + (1-\delta^i)(E_t^i)^\rho]^{1/\rho}$$

$$(14)\quad NE_t^i = A_2^i(K_t^i)^{\alpha_i}(L_t^i)^{(1-\alpha_i)}$$

$$(15)\quad E_t^i = A_3^i AEEI^i(qcoal_t^i)^{\beta_i}(qoil_t^i)^{\gamma_i}(qngas_t^i)^{\theta_i}$$

$$(16)\quad NE_t^{world} = \sum_{i=1}^{I} NE_t^i$$

$$(17)\quad E_t^{world} = \sum_{i=1}^{I} E_t^i$$

$$(18) \quad K_t^{world} = \sum_{i=1}^{I} K_t^i$$

$$(19) \quad qcoal_t^{world} = \sum_{i=1}^{I} qcoal_t^i$$

$$(20) \quad qoil_t^{world} = \sum_{i=1}^{I} qoil_t^i$$

$$(21) \quad qngas_t^{world} = \sum_{i=1}^{I} qngas_t^i$$

where the superscript i: $i = 1, 2, 3, ... I$, represents regions. The variable definitions correspond to those in equations (1) through (11) of the global macroecoconomic model. The unknown variables in each time period are the regional levels of output, Q_t^i, composite non-energy inputs, NE_t^i, composite energy inputs, E_t^i, capital stock, K_t^i, levels of coal, $qcoal_t^i$, oil, $qoil_t^i$, natural gas, $qngas_t^i$, and other fuel types that might be considered.

Two possible approaches might be followed to solve the above system of equations. Alternative A: Under this approach, each region's macroeconomic variables are determined optimally. The corresponding global values are obtained by aggregation of the regional levels. Alternative B: Here the outputs of the global macroeconomic model, described in table 1, are used to project the corresponding regional values for the unknown variables. The changing intertemporal share of each region in world economic output, for example, would be estimated using historically observed panel data.

Thus, a framework will be established to take account of regional variations in production elasticities, and the disparate contributions of the various factors of production to long-term growth. This will facilitate the determination of region specific welfare impacts, defined as the sum of producers' and consumers' surplus, of alternative climate change mitigation and adaptation strategies.

The units of analysis are the following major countries or country groupings:

U.S.	Central and Southern Africa
Canada	India
Mexico / Central America / Caribbean	China
South America	Indonesia
Western Europe	Japan
Eastern Europe	Southeast Asia (other)
Former Soviet Union	Oceania
S.W. Asia / Middle East / N. Africa	

One of the advances we offer over many other integrated assessment models is a GCM analysis at a very high degree of resolution. However, our 100 km grids are finer than the boundaries of any meaningful political jurisdiction, i.e., of key decision-making units in global warming negotiations. Therefore, we have chosen major country or countries groupings.[3] A complete list of the countries included in each region is given in Appendix D.

II.2 GHG and Aerosol Concentration Module

The purpose of this module is to compute the concentration of radiatively active gases and aerosols that may be perturbed either directly or indirectly through human actions. CO_2, CO, and

[3] Many of the country groupings are chosen to reduce the proliferation of units of analysis, but most are relevant to decision-making. For example, the European Union often undertakes actions as a block, and many developing countries have banded together to provide themselves with political clout they would not otherwise have.

SO_2 emissions will be specified from the Macroeconomic Module as a function of the amount and type of fossil fuel burning. The emission rates of CFCs, HCFCs, HFCs, FCs, and the natural component of CH_4, N_2O, and NO will be exogenously specified. The anthropogenic fraction of methane emissions will be based upon predicted rice production, domestic animal population[4], coal mining, natural gas production, land fills, and biomass burning[5]. Anthropogenic N_2O emissions will be computed on the basis of ecosystem composition, fossil fuel burning, and land use. Globally homogenous atmospheric concentrations of the aforementioned gases will be assumed. However, SO_4 aerosol concentrations will be predicted on a regional basis as a function of regional SO_2 emission rates.

Uptake of anthropogenically produced CO_2 will be computed through the use of a 50-level oceanic sub-model based on Siegenthaler (1983) coupled with a 75-box (15 regions x 5 reservoir types) terrestrial biosphere sub-model based on Sarmiento et al. (1995) [for a complete description of the carbon cycle model see Kasting and Schultz (1996); Schultz (1996)]. Several enhancements have been made to the Siegenthaler (1983) model, including: 1) replacing the buffer factors with explicit carbonate/borate chemistry, 2) adding particulate fluxes of carbonate and organic carbon, 3) adding realistic ocean hypsometry, and 4) including weathering of terrestrial and silicate rocks. With these changes the ocean sub-model exhibits CO_2 uptake rates similar to those calculated by Siegenthaler and Oeschger (1987) and Maier-Reimer and Hasselman (1987).

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[4] Rice and animal production are estimated in the agriculture sub-module. Corresponding methane emissions will be scaled using the estimates in Watson et al. (1990) and the references therein.

[5] Coal mining and natural gas production are estimated in the Macroeconomic Module. Land fills and biomass burning will be estimated as a function of population. Corresponding methane emissions will be scaled using the estimates in Barns and Edmonds (1990).

The terrestrial sub-model will represent the uptake of anthropogenic CO_2 in each of the DSA model's 15 regions. In each region, reservoirs for metabolic and structural carbon of live vegetation and litter, as well as soil carbon, will be represented. Included in the terrestrial sub-model are functions describing the dependence of decomposition on temperature. In addition, the model allows for carbon sequestration as a result of CO_2 fertilization and climate change. The reservoir sizes will also vary as a function of the vegetation changes predicted by the natural ecosystem and agriculture sub-models. In this manner, this module attempts to account for the regional impact on the carbon cycle induced by spatially heterogeneous climate change.

Uptake of atmospheric methane, which occurs primarily through tropospheric reactions with OH [445 Tg(CH_4)/yr] (Prather et al., 1995), will be based upon the model of Osborn and Wigley (1994). The relatively slower stratospheric (40 Tg(CH_4)/yr) and soil (30 Tg(CH_4)/yr) methane uptake as well as N_2O, NO, CFC and FC uptake will be modeled using first order kinetic reactions. The removal of O_3 will be determined through a functional dependency with N_2O (which controls NO_x formation) and halocarbons. HCFCs and HFC uptake will functionally depend upon the OH concentration (which depends upon the concentration of several gases including CO, CH_4, NO_2, and SO_2).

II.3 Climate Change Module

In the first phase of the proposed study, wherein the optimal GHG concentration targets are estimated, a series of equilibrium GCM simulations will be conducted using the National Center for Atmospheric Research (NCAR) Community Climate Model (CCM). The long-term marginal benefits function will be computed in the Impact Assessment Module using output from

CCM simulations of 1, 2, 4, 8, and 16 times[6] the pre-industrial atmospheric CO_2-equivalent[7] concentration. These equilibrium simulations will incorporate corresponding estimates of regional aerosol concentrations based upon the approximate[8] GHG emission rate that will produce the desired constant atmospheric GHG concentration.

In the second phase of the study, the transient climate response will be computed from the changes in radiatively active gas concentrations determined in the GHG and Aerosol Concentration Module. Using a climate change data base, compiled from a series of transient runs of the National Center for Atmospheric Research coupled ocean-atmosphere GCM and adjusting for local aerosol effects, the transient climate change will be estimated on a global grid.

The net radiative forcings from CO_2, CH_4 and N_2O, HFCs, FCs, CFCs, HCFCs, and O_3 will be calculated using the concentrations predicted in the GHG and Aerosol Concentration Module and using IPCC radiative parameters (Shine *et al.*, 1995, and the references therein). The radiative effects of sulfate aerosols will be regionally estimated based upon the regional distribution of emissions and the GCM results of Taylor and Penner (1994).

The objective of the Climate Change Module will be to produce estimate of climate change on a 4.5° latitude by 7.5° longitude grid that have intra-annual temporal characteristics

[6] The potential fossil fuel carbon reserves have been estimated to be as high as 9,500 to 20,000 gigatons of carbon (Manne and Richels, 1990; Reilly *et al.*, 1987; Nordhaus and Yohe, 1983). Calculations made with a box-diffusion model of the carbon cycle indicate that the atmospheric concentration could reach more than 18 times the pre-industrial level if 15,000 gigatons of carbon are emitted (Schultz, 1996).

[7] 'CO_2-equivalent' refers to the atmospheric concentration of CO_2 that would produce the same net radiative forcing as the given concentrations of all non-CO_2 GHGs.

[8] It is an 'approximate' emission rate because the emission rate must decline slightly with time in order to produce a constant atmospheric CO_2 concentration

robust enough for use in crop growth models. Previous end-to-end IA models have typically used simple, regionally aggregated predictions (e.g. Manne *et al.*, 1995) that use temperature as a proxy for climate change as a whole, or zonally averaged 2-D climate model results (e.g. Alcamo *et al.*, 1994) that are used to scale equilibrium GCM simulations[9]. While the recent use of 2-D climate models to scale equilibrium GCM results represents an improvement over earlier climate change representations, the equilibrium GCM methodology neglects the importance of oceanic interactions in forming the spatial pattern of transient climate change. By influencing the air-sea contrast, the thermal lag of the oceans during transient climate change will likely impart a pattern of climate change that is different from the patterns predicted by GCMs when the oceans and atmosphere are at equilibrium with respect to each other. Thus, errors arise when equilibrium GCM simulations are applied to transient climate change scenarios. However, coupled ocean-atmosphere GCMs (OAGCMs), which include 3-D representations of both the oceans and atmosphere, are the tools most capable of capturing the dynamic importance of the oceans in transient climate change.

Because it would be too time consuming to interactively run a coupled ocean-atmosphere GCM (or even a typical atmospheric GCM) with each integrated assessment model experiment, a climate change data base will be constructed from multiple transient OAGCM runs and used interactively with the DSA model tier. The OAGCM runs comprising the climate change data base will be conducted with different and temporally varying gaseous and aerosol radiative forcings. It

[9] MAGICC (Hulme *et al.*, 1995) is being designed to utilize climate change scenarios input from the GCM-based SCENGEN (Santer *et al.*, 1990). However, the high degree of interactive utilization of GCM information is a unique innovation of the IA model proposed here. In addition, the MAGICC/ESCAPE model (Rotmans *et al.*, 1994) is not a full end-to-end IA model in that it lacks any macroeconomic detail.

is unlikely that the time path of GHG and aerosol forcing used in the DSA model runs will exactly match the forcings used in the OAGCM runs. Therefore, during a DSA model run the climate change for a specific time and grid cell will be determined through parametric interpolation of the previously created OAGCM runs. This parametric approximation will take into account the instantaneous and time history of radiative forcing from GHGs and aerosols.

It has been shown that GCMs do not always produce a realistic representation of the intra-annual temporal character and mean state of the present climate (Gates *et al.*, 1996). To deal with these deficiencies we will utilize the methodology of Robock *et al.* (1993). In this methodology, a GCM simulation of the present climate condition[10] is compared to current observations of the climate. For those grid cells where the model error, determined through a model-observation comparison, is below a specified threshold, the simulations of future climate are used in their unaltered state. However, where the model error exceeds the threshold tolerance, two steps will be taken to make the simulations of future climate more suitable for use in climate impact assessments. First, in those regions with substantial model-observation discrepancies, the GCM predictions of future climate will be averaged over clusters of grid cells, approximately 4-12 cells in size. These clusters will be delineated based upon bioclimatic similarities (e.g. Holdridge life zones). The basis for this spatial averaging procedure lies in findings from several studies which conclude that GCMs more accurately simulate the present climate at the regional scale than at the scale of individual grid cells (see references in Gates *et al.*, 1996). Second, in those grid cells where the present climate is poorly simulated, the future climate change anomaly will be

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[10] The GCM simulation of the current climate will be carried out by 'spinning up' the GCM from a pre-industrial state, subject to realistic increases in GHGs and aerosols.

computed by subtracting the GCM simulations of future climate from the GCM simulations of the present climate. These GCM climate change anomalies, which are regionally averaged, will be added to the observed climatological intra-annual record at each grid cell in that region. Thus, the interannual change predicted by the GCM will be incorporated with observations to specify a more realistic intra-annual temporal character of climate change.

In this manner, a grid-scale prediction of climate change will be produced that corresponds to the gaseous and aerosol emissions and concentrations predicted by the Macroeconomic and GHG and Aerosol Concentration Modules. Our IA modeling group is uniquely qualified to carry out this phase of the project based upon the collective experience we possess modeling past, present, and future climate using GCMs (e.g. Barron, 1995a and 1995b; Barron *et al.*, 1995; Jenkins and Barron, 1996; Schultz *et al.*, 1992). Furthermore, the Penn State Earth Systems Science Center is well-equipped to carry out this CPU-intensive phase of the IA modeling effort, due in part to the Cray J90 16 processor supercomputer and the extensive network of high performance Unix workstations. Soon to be initiated is a joint Penn State - NCAR OAGCM modeling study of transient climate change. This study will provide the transient OAGCM simulations required in the climate change prediction methodology described above.

II.4 Impact Assessment Module

In the Impact Assessment Module of our DSA model tier, the primary focus will be to incorporate the *dynamic* nature of climate change impacts through explicit modeling of individual factors. It is imperative to transcend static impact analyses because it is highly likely that many of the impacts will be non-linear with respect to not merely the magnitude, but also the rate and timing of climate change (Pearce *et al.*, 1996). The explicit modeling of individual factors relevant to climate change impact also enables the PCIA model to estimate the damages from extreme levels of climate change (e.g. quadrupling and octupling of the present atmospheric CO_2-equivalent concentration). These are areas of research that have received little attention in the scientific literature (Pearce *et al.*, 1996).

The impact estimates in each of the Impact Assessment sub-modules will be conducted either on the scale of individual countries or on a global grid corresponding to the one used in the Climate Change Module. The results from each of the Impact Assessment sub-modules will be aggregated to the regional scale (i.e. 15 regions comprising the world) before being transferred back to the Macroeconomic Module, where they will be incorporated into the utility and the production functions.

II.4.1 Agriculture

The impact of future climate change on agriculture is sometimes estimated as the reduction in yields to the present agricultural distribution. As several studies have pointed out (e.g. Easterling *et al.*, 1989; Rosenberg, 1992; Mendelsohn *et al.*, 1994), if adaptations (i.e. corrections towards optimal distributions and methodologies) to climate change are not accounted for, an overestimation of the impacts will result. However, the methodology to be employed here first estimates the *optimal* crop distributions and then the net impacts. Towards this end a series of crop and livestock models and a global food trade model will be used in an iterative procedure to estimate post-adaptive impacts.

The IBSNAT (International Benchmark Sites Network for Agrotechnology Transfer) wheat (Ritchie and Otter, 1985; Godwin *et al.*, 1989), maize (Jones and Kiniry, 1986), rice (Godwin *et al.*, 1992), and soybean (Jones *et al.*, 1989) models will be employed to estimate future crop yields at several representative sites within each of the 15 regions (after Parry and Rosenzweig, 1993, and Rosenzweig *et al.*, 1995). Planting dates will be chosen as to maximize agricultural production. Livestock meat and milk production will be predicted using empirically developed climatic relationships (e.g. Klinedinst *et al.*, 1993). At each time step in the IA model the crop and animal yields will be computed, the results of which will be input to a global food trade model (Fischer *et al.*, 1988), thereby providing estimates of food prices and the number of people at risk from hunger. This food trade model, the Basic Linked System (BLS) model, is an applied general equilibrium model which takes into account trade barriers, price rigidities, and mark-up pricing. Once an initial calculation of food prices and hunger risks are made, crop type, crop acreage, livestock type and livestock amount will be incrementally varied and the agricultural models and the global food trade model will be re-run. By comparing the global welfare change resulting from the incremental change in the independent variables, a vector of partial differentials of welfare with respect to crop and animal distributions will be established. This vector, which indicates the direction towards an improved crop and animal distribution, will be used as the input into a new iteration of the yield and trade models. This procedure will be iterated upon until no further welfare increases are possible, thereby establishing an optimal crop and animal distribution for each model time step. While this methodology will certainly not provide an exact prediction of future agricultural practices, it will produce much more plausible results than to assume the absence of competitive agricultural adaptations. We will examine the sensitivity of the results to differing degrees of trade liberalization and agricultural innovation (e.g. introduction of drought resistant crop strains).

Welfare changes due to agricultural impacts will be computed as a function of hunger risk, food prices, and food production. The demand for food, used in determining hunger risk, will be estimated based upon the methodology of Zuidema *et al.* (1994). In this methodology previously determined empirical relationships relate per capita food consumption of major food types to income, taking into account the elasticities of consumption with respect to income.

Agricultural changes predicted in this sub-module will influence methane emissions and the carbon balance in the GHG Concentration Module.

II.4.2 Natural Ecosystems

Strong empirical relationships that have been observed between the distribution of natural ecosystems and climate (e.g. Emanuel *et al.*, 1985; Schultz and Halpert, 1993 and 1995; and Prentice *et al.*, 1993). However, other factors such as soil characteristics (e.g. Raich and Schesinger, 1992), nitrogen limitation (e.g. Rastetter *et al.*, 1992), and CO_2 fertilization (e.g. Wullschleger *et al.*, 1995) also exert strong influences on ecosystems. The phytogeography and primary productivity model of Woodward *et al.* (1995) incorporates all of these factors and will be used in the proposed model. This natural ecosystem model will be driven by climatic variables computed in the Climate Change Module at a resolution of 4.5° x 7.5°. The vegetation type and characteristics of regions dominated by human influence (e.g. agricultural land) will be exogenously specified. Although the Woodward *et al.* model generally represents the distribution of vegetation characteristics quite realistically, there are a few areas where it is likely in error. Thus, only net *changes*, relative to results produced for the present day, will be used as input to other portions of the PCIA model.

Incorporating the methodologies of Titus (1992) and Fankhauser (1995), the net changes in value and production to the forestry industry will be computed, taking into account the value and amount of affected timber and associated costs.

Other direct losses resulting from ecosystem changes will be extremely difficult to evaluate, including those related to non-timber products, recreation, and medicine. In addition, indirect values (e.g. water quality buffering, air pollution reduction, and micro-climatic effects) are also difficult to quantify, as are those for the option and existence value of individual ecosystems and biodiversity as a whole. The problems associated with globally quantifying these assets are several-fold, but include the following: (1) a systematic, global identification of these assets is lacking; (2) a loss in one area may be accompanied by a gain in another; (3) empirical willingness-to-pay case studies are controversial and subject to large errors; and (4) the manner in which these assets should be temporally and spatially weighted[11] has yet to be clearly defined. In light of these numerous uncertainties, we will establish a model framework in which several alternative formulations and assumptions can be explored.

The changes predicted by this sub-module will be fed back into the GHG and Aerosol Concentration Module to estimate terrestrial vegetation impacts on the CO_2, CH_4, and N_2O budgets.

II.4.3 Space Heating and Cooling Energy Usage

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[11] These weights address the notion that societies that are spatially and temporally more proximal to a particular asset will tend to value it more than societies that are more distal.

While regional and country-wide estimates have been made of the energy usage changes that may result directly from climate change (e.g. U.S.: Smith and Tirpak, 1989; U.K.: Parry and Read, 1988; Germany: Gertis and Steimle, 1989; Japan: Nishinomiya *et al.*, 1989; and FSU: Hashimoto *et al.*, 1990), a rigorous, global study has not been conducted. In this sub-module first-order predictions of space heating and cooling energy usage changes will be made for each country on the basis of functions driven by temperature information predicted by the Climate Change Module.

The space heating energy usage functions that will be used are based upon empirical functions derived from current end-use energy consumption (e.g. USA: EIA, 1995; OECD: Schipper *et al.*, 1996; China: Xiaohua and Zhenming, 1996; developing nations: Ang, 1990?). The mathematical representation of space heating for a given region, j, at time, t, is given as follows:

(22) $$\text{Space Heating}_{j,t} = HDD_{j,t} * \Lambda_j * L_{j,t} * \Delta EE_{j,t}$$

where HDD are the heating degree days[12], Λ is the space heating carbon intensity [BTU / (person

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$$CDD = \sum_{i=1}^{N} (T_{max} - T_s), \text{ where } T_{max} > T_s$$

$$HDD = \sum_{i=1}^{N} (T_w - T_{min}), \text{ where } T_{min} < T_w$$

T_{max} and T_{min} are the daily maximum and minimum temperatures. T_s and T_w are summer and winter threshold temperatures.

* HDD)] obtained from previous energy end-use studies, L is the population[13], and ΔEE is the fractional change in energy efficiency prescribed using the estimates contained in the 1994 IPCC report (Alcamo et al., 1995). The ΔEE coefficients that will be used represent the energy efficiency of regional economies as a whole. While space conditioning energy efficiencies may not change at the same rate as the energy efficiency across all sectors, the IPCC estimates are the best available for the application described here.

Space cooling energy expenditure data are not as readily available for regions outside the US. There are data available for Malaysia and the Phillipines (Sathaye and Meyers, 1990?) that describe space cooling energy expenditures as a function of per capita income. The data for the U.S., which also describe the changes in space cooling as a function of cooling degree days (CDD), will be used to derive the slope of the energy usage - CDD relationship. This function will be tuned to predict space cooling energy usage as a function of CDD, per capita income (Ypc), and present and future energy efficiency:

$$\text{(23)} \qquad \text{Space Cooling}_{j,t} = CDD_{j,t} * L_t * Ypc_{j,t} * \phi * \Delta EE_{j,t} * EE_{j,\,present}$$

where ϕ [BTU / (money * CDD * person)] is a coefficient that encompasses the direct relationship between CDD and space cooling energy expenditures, predicted from the U.S. data. Both equation 23 and the equation describing space heating include the assumption that space conditioning energy expenditures are linearly proportional to CDD and HDD. This is supported

[13] Present population data for the study will be derived from the five minute by five minute gridded data of Tobler *et al.* (1995).

by our initial analysis of the EIA (1995) end-use data.

The changes in energy usage predicted in this portion of the model will be fed back into the Macroeconomic module.

II.4.4 Morbidity and Mortality

An analogous technique to the one outlined above will be used to estimate changes in morbidity and mortality resulting from climate change[14] using previously determined empirical relationships (e.g. Kalkstein, 1991; Kalkstein, 1993; Kalkstein and Smoyer, 1993; Kalkstein and Tan, 1995; Schwartz and Marcus, 1990; Dockery *et al.*, 1993). Climate change information, including heating and cooling degree days, will be supplied to these relationships from the Climate Change Module at the 4.5° x 7.5° grid resolution, in addition to regional SO_2 concentrations from the GHG and Aerosol Concentration Module. Through the use of simple scaling relationships, SO_2 will be used as a proxy for other tropospheric pollutants that affect morbidity and mortality.

The morbidity and mortality estimates made in this manner will be converted to monetary units according to previous valuation studies (e.g. Viscusi, 1993; ORNL/RFF, 1994). Similarly, changes in hunger risk estimated in the agricultural impact sub-module will be transformed into estimates of morbidity and mortality and subsequently converted to a uniform monetary metric.

While this methodology will not explicitly model individual disease vectors (*a la* Martens *et al.*, 1995), it will mark a significant step forward in incorporating health impacts in IA models

[14] Morbidity and mortality rate changes caused by other factors, including agricultural change and sea level rise, will be addressed in their respective sub-modules. The sub-module described in section II.4.4 only deals with morbidity and mortality rate changes that are directly linked to climate change.

due to the spatial resolution at which the assessment will be carried out. Subsequent version of the PSCIA model will incorporate a higher level of sophistication with regards to health impact assessment, by estimating the numbers of people exposed to various climate related health risks and disease classes[15].

II.4.5 Sea Level Rise

Sea level changes will be predicted as a function of the globally averaged temperature change using the sea level model of Titus and Narayanan (1995). Later versions of the IA model will take into account local subsidence rates.

To estimate sea level rise damages we will draw upon previous studies that have estimated impacts for various regions and sea level rise benchmarks. However, in estimating the economic impact of sea level rise, we will also take into account the turnover time of the affected capital. It will be assumed that much of the requisite adaptive measures will be carried out only as old coastal infrastructures need to be replaced. The costs of adaptation, retreat, and protection will be manifested in the Macroeconomic Module in the form of reductions in economic output. This methodology will allow for the economic impact of a higher sea level to greatly diminish, once the response measures have been enacted. This framework for quantifying sea level rise impacts encompasses the probable economic impact more satisfactorily than the commonly made assumption of a damage term that is strictly proportional to sea level and temporally invariant if sea level stabilizes.

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[15] Borrowing from Martens' globally aggregated MIASMA (Model for the health Impact Assessment of Man-induced Atmospheric changes) framework (Martens, 1996).

II.4.6 Other Impacts

Economic losses from decreased water supplies (resulting from a net decrease in precipitation minus evaporation in addition to salt-water intrusion of coastal aquifers) will be estimated as a function of the regional climate change predicted by the Climate Change Module and calibrated using the estimates of Cline (1992), Titus (1992), and Fankhauser (1995).

Although a few valuation estimates exist pertaining to the effect of climate on human amenity (Hoch and Drake, 1974; Gyourko and Tracy, 1991; and Leary, 1994), it is not clear that a meaningful global quantification of this relationship is possible at present. In this light, initial experiments will test the model's response to various degrees of per capita amenity sensitivity to climate change. Thus, the framework for amenity impacts will be established so that as more empirical evidence becomes available it can be readily incorporated into the DSA model tier.

While willingness-to-pay (WTP) studies have shown that biodiversity and preservation of individual macrofaunal species are entities to which significant non-market values are attached (e.g. Pearce, 1993), it is extremely difficult to estimate to what extent they will be affected by climate change due in part to the adaptability of biological systems. Another factor that is extremely difficult to assess is the impact of potential changes in the frequency and/or intensity of extreme storm events. While some studies indicate that the occurance of storm events will increase (e.g. Haarsma *et al.*, 1993; Houghton, 1994), others argue that it is not clear that the frequency and/or magnitude of extreme events will increase (e.g. Raper, 1993; Bengtsson et al., 1995).

II.5 Policy Analysis Module

This module first makes sure the data and functional relationships of the other modules are appropriate to the desired spatial level and then performs policy analyses. The outputs of the various modules will be aggregated as appropriate. For the Impact Assessment Module this involves straightforward additions or averaging over larger areas, while for the Macroeconomic Module it involves a combination of direct partitioning and use of supplemental data on greenhouse gas mitigation in each region.

The Impact Assessment Module produces benefit functions associated with GHG mitigation. Ideally, the mitigation level would be set by a benefit-cost criterion, i.e., the point at which net benefits of actions would be maximized. At this point, global marginal benefit (MB) is equal to global marginal cost (MC), as indicated in Figure 8 for a two-century example. The intersection of these functions gives the global optimum GHG reduction level or percentage, as well as the value of this undertaking at the margin. The global abatement requirement is then apportioned to individual countries. The efficient outcome is that which equalizes the marginal cost of abatement across all units, at the value determined by the global marginal benefit and marginal cost intersection. Clearly, if marginal abatement costs differ across countries, so will abatement levels. In fact, as indicated in Figure 8, countries with relatively lower abatement costs would be asked to undertake relatively higher abatement percentages for the sake of global efficiency (China 32 tons and the U.S. 18 tons). Under such a system of inflexible quotas, or fixed emission limits, this raises obvious questions of equity, or fairness, especially if developing countries have relatively flatter GHG mitigation cost curves than industrial countries.[16]

[16] The main reasons are that they have very sophisticated equipment in place and more inherent inefficiencies in resource use (especially energy). Alternative perspective on the relative position of developing country and industrialized country mitigation cost curves (see, e.g., Khanna and Chapman,

There are other policies that can bring about the global optimum in ways that ensure global efficiency (but at lower administration costs), allowing for more individual country choice, and better addressing equity issues. Two such approaches are carbon tax and tradeable permit instruments.

The carbon tax is set by the global marginal benefit and global marginal cost intersection and allows each country to respond with more freedom of choice. When confronted with paying the tax or undertaking GHG mitigation, countries will choose the lower cost alternative and voluntarily undertake GHG mitigation levels consistent with global efficiency (the same level as illustrated by our inflexible quota example above). However, the carbon tax revenue can be redistributed in such a manner as to address equity issues.

In a similar vein, countries can be assigned permits to emit GHGs and then be allowed to trade them (actually identical to a system of tradeable quotas). The equilibrium permit price is again equal to the global MB and MC intersection and is equivalent to the carbon tax level. Countries with marginal abatement costs higher than the permit price will buy permits from countries with marginal abatement costs lower than the price. In the example of Figure 8, if China and the U.S. are initially assigned permits equal to 75% of their baseline emissions, the U.S. will buy 12 permits from China. Equity issues can be addressed by the initial assignment of permits or by side-payments following trading.

The problem that arises is that there is no single best definition of equity. However, we can simulate the individual country welfare implications of alternative equity principles as listed in table C.1 (the same principles can be applied to analyzing the redistribution of carbon tax

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1996a) will be examined as well.

receipts).[17] Rose and Stevens (1993; 1996) have developed a set of non-linear programming models to perform the simulations. The models are distinguished according to whether equity principle are applied to the initial assignment of permits or the final welfare outcomes. The Rose-Stevens analysis, previously undertaken in a static context,[18] will be transformed into a dynamic formulation as part of the research so that it is fully consistent with the dynamic nature of our IA system.[19]

In addition, the MC curves used in most geographically differentiated policy simulations to date pertain only to partial equilibrium aspects, i.e., the direct costs of GHG mitigation measures, including conservation, inter-fossil fuel substitution, use of non-renewables, carbon absorption, and climate engineering.[20] These can all generate second-order, or general equilibrium, economic effects, e.g., changes in prices, investment levels, imports, and government expenditures. General equilibrium considerations, which can significantly raise or lower the MC curves (see, e.g., Jorgensen and Wilcoxen, 1993; Rose and Lin, 1995), will be modeled in a manner consistent with our Macroeconomic Module. The importance of this aspect will be determined by comparisons of

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[17] In fact, the Market Justice case, where permits are auctioned off to the highest bidder, rather than granted freely, is equivalent to the carbon tax revenue redistribution issue.

[18] The Rose-Stevens model does allow for some dynamic aspects. For example, emission reductions can be based on cumulative and not just current emissions. Also, the effect that current mitigation expenditures may have in reducing future economic growth can be incorporated as well.

[19] Previous analyses have yielded some valuable insights. For example, large subsets of seemingly very different equity principles have very similar welfare outcomes. This means that tensions at the bargaining table might significantly be reduced if policy-makers look beyond initial allocations. At the same time, some seemingly reasonable equity principles have untenable welfare implications (e.g., the welfare outcome for the Egalitarian principle stipulates negative net benefits for the U.S. and Western Europe in the tens of billions dollars per year). See also Chapman and Drennan (1990).

[20] Also, more specific policies can be analyzed, such as development of drought-resistant crop strains, building of seawalls, and other adaptation methods.

simulations of optimal policies under partial equilibrium and general equilibrium conditions separately.

Several studies have discussed the importance of taking into account international differences in the burdens and benefits associated with climate change (e.g. Schelling, 1995; Azar and Sterner, 1996). In particular, income dependent variations in marginal utility must be considered in a rigorous analysis of the issue. Moreover, the value of certain non-market impacts has been estimated to be lower in developing nations (e.g. Parikh *et al.*, 1994; Pearce *et al.*, 1996). Therefore, the PCIA model will include regionally dependent utility functions that are characterized by regionally dependent discount rates, in which the discount rate varies as a function of economic growth and wealth. This will facilitate further exploration of the policy potentials and implications for international burden and benefit sharing.

Following the suggestion by Tol (1994) we will examine the sensitivity of the model to incorporating damages to intangible goods (i.e. goods that are inputs to human welfare that are not marketed and priced) directly in the utility function. Furthermore, we will assess the implications of increasing the value of intangible damages in proportion to per capita income.

One of the most important parameters in an optimal growth model is the pure rate of time preference. This parameter has implications for both the efficiency and equity (both international and intergenerational) of the model's solution. A high pure rate of time preference tends to shorten the effective time horizon of the economic problem by reducing the present value of temporally distant utility (e.g. Khanna and Chapman, 1996). On the other hand, a low pure rate of time preference leads to exaggerated investment rates because lower yielding investments appear to be more desirable, relative to the rate of time preference rate (e.g. Manne, 1995). The conflict between dynamic equity and efficiency is, however, muted in a target-oriented approach (such as the one proposed to be carried out with the PCIA model), because resource levels[21] sufficient for sustainable economic activity are guaranteed (Norgaard and Howarth, 1991). Nonetheless, we will examine the differential results produced from simulations using the range of pure rate of time preference values discussed by Arrow *et al.* (1996) in the 1995 IPCC report, including values determined through both descriptive and prescriptive means.

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[21] Atmospheric GHG concentrations can be viewed as proxy for a wide range of environmental resources. In other words, GHG levels determine, in part, the availability of resources such as water availability, agricultural products, and a climate that is tolerable from the human perspective.

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APPENDIX A.

It would be quite CPU-time intensive to include the full complexity of the DSA model tier in a dynamically optimizing context. Roughly 1×10^4 to 5×10^4 complete iterations are required using a quasi-Newton approximation technique to compute the optimal temporal trajectory of GHG emission reductions and investment for a 500 year model run with 10 year time steps. It is estimated that the elements of the Impact Assessment Module, which themselves are solved through iterative techniques, will require on the order of several minutes on a 16 processor Cray supercomputer to converge for a single 500 year iteration. Therefore, months of dedicated computer time would be required to produce a single dynamic optimization run. This estimate, however, assumes that the decision variables (i.e. investment and GHG emission reduction) are globally aggregated. Any increase in complexity (e.g. spatial dimensionality) will greatly increase the run-time. The following rule-of-thumb can be used to estimate changes in run-time:

$$\textit{Run-time} \;\; \alpha \;\; [(\textit{nr. of time steps}) * (\textit{nr. of decision variables per time step})]^2$$

For example, a run in which investment and GHG emission reduction are determined separately for the developed and undeveloped countries (i.e. a world consisting of two regions), the run-time will increase approximately by a factor of 4 relative to a globally aggregated simulation.

Although a dynamically optimizing version of the model is theoretically feasible, a reduced-form version has a number of advantages as a result of its shorter run-time. The simplifying parameterizations of the reduced-form version will incorporate most of the relevant variability of the full model, while reducing the run-time by a factor of 10^2 to 10^4. Some of the advantages of this time saving are: (1) the model will be portable for use by other researchers and policy makers; (2) a much wider range of model assumptions can be explored; (3) model improvements can be quickly implemented; (4) model errors can be quickly corrected; and (5) we will be able to conduct a series of simulations in which the assumptions in one experiment are based upon the outcome in the previous simulation.

One of the key contributions of the reduced-form dynamically optimized model tier will be its inclusion of the dependence of impacts on the rate of climate change (in addition to the magnitude of the climate change). Although a few other integrated assessment models have predicted climate change impacts as a function of the rate of climate change (e.g. Hope *et al.*, 1993; Fankhauser, 1994), two of the key advantages of the proposed model are: (1) the rate dependency is derived as an explicit function of specific impacts; and (2) the proposed model is capable of dynamic optimization.

APPENDIX B.

A REVIEW OF INTEGRATED ASSESSMENT MODELS FOR CLIMATE CHANGE

Table B.1: Optimizing Models

Model/Authors	Maximized Variable	Control Variable
RICE (Nordhaus & Yang, 1996)	*Non-cooperative scenario*: each region maximizes its utility function defined as the sum of the discounted value the log of its per capita consumption times its population *Cooperative scenario*: global welfare defined as the weighted combination of the regional utility functions (defined above)	Regional investment levels; regional control rate for carbon emissions;
DICE (Nordhaus, 1994)	Sum of discounted value of the log of global per capita consumption times global population	Global investment level; global control rate for carbon emissions;
DICAFE (Khanna & Chapman, 1996)	Same as DICE	Same as DICE
MERGE (Manne, Mendelsohn, & Richels, 1995)	Sum of discounted value of log of aggregate consumption for each region	Regional investment levels
Wigley, Richels, & Edmonds (1996)	Not applicable (simulation model)	Not applicable
CETA (Peck & Teisberg, 1992 & 1995)	Sum of discounted value of the log of global per capita consumption times global population	Global investment level; energy use level;

Table B.2: Determinants of Energy Use

Model/Authors	Definition of Energy	Factors Directly Affecting Energy Use
RICE (Nordhaus & Yang, 1996)	Not explicitly modeled Implicit in regional CO_2-GNP ratios.	Prices not explicit; finite fossil resources not explicit; regional output; growth in total factor productivity and decarbonization rate;
DICE (Nordhaus, 1994)	Not explicitly modeled. Implicit in CO_2-GNP ratio.	Same as RICE. Output and productivity growth aggregated to global level.
DICAFE (Khanna & Chapman, 1996)	Coal, gas, & synfuel (backstop) modeled as Cobb-Douglas demand functions. Oil production increases near term according to Hotelling-type resource depletion model.	*Coal, gas, & synfuel demands* are a function of energy prices, population, and per capita income. *Oil production* depends on global per capita income & population; remaining oil resources; extraction cost; cost of backstop;
MERGE (Manne, Mendelsohn, & Richels, 1995)	Energy is a factor of production in a nested CES production function. Energy defined as a Cobb-Douglas function of electric & non-electric energy.	Oil prices dependent on inelastic supply; regional output and population; supply cost; technology expansion & decay factors; remaining coal, oil, and gas resources; oil use path exogenously fixed & monotonically declining; AEEI; ESUB;
Wigley, Richels, & Edmonds (1996)	Not explicitly modeled. Implicit in emission path.	None
CETA (Peck & Teisberg, 1992 & 1995)	Same as MERGE	Same as MERGE. Output & population are aggregated to global level.

Table B.3: Global Damage Characterization

Model/Authors	Functional Form	Geographical Specification
RICE (Nordhaus & Yang, 1996)	Quadratic in temperature rise	6 or 10 regions. Exponent same across regions. Regionally calibrated scale factor varies.
DICE (Nordhaus, 1994)	Quadratic in temperature rise	Global
DICAFE (Khanna & Chapman, 1996)	Same as DICE	Same as DICE
MERGE (Manne, Mendelsohn, & Richels, 1995)	*Market damage:* quadratic in temperature rise *Non-market damage:* depends on willingness to pay to avoid ecological damages. WTP depends on per capita income & temperature rise according to an S-shaped function.	*Market damage:* Fraction of GDP lost due to 2.5°C warming is twice as high in developing countries *Non-market damage:* WTP is higher for developed countries. WTP independent of regional location of damage.
Wigley, Richels, & Edmonds (1996)	No damage assessment	Not applicable
CETA (Peck & Teisberg, 1992 & 1995)	Cubic in temperature rise relative to pre-industrial levels. 1992 version included linear specification. 1995 version scales damage function by time dependent index of population levels.	Exponent is the same for all regions. Scale factor calibrated such that a 3°C rise in temperature causes a 2% loss in regional gross outputs.

Note: All models surveyed characterize climate change related damage as a single equation in two variables: loss in GDP, and temperature rise. The only exception is MERGE which distinguishes between market and non-market damages. Details are included in the table above.

Table B.4: Typical Functional Forms Employed for Three Major Variables

1. *Maximized variable*

$$U(\cdot) = \sum_{t=0}^{T} \frac{1}{(1+r)^t} \ln(C_t)$$

where U(•) represents the level of utility, r is the discount rate, and C_t is either the aggregate consumption level, or the level of per capita consumption. CETA and MERGE use the function shown above. In the case of RICE, DICE, and DICAFE, where per capita consumption is used, the log term is multiplied by the population level.

2. *Damage characterization*

$$\frac{D_t}{Q_t} = \alpha(\Delta T)^{\beta}$$

where D_t/Q_t is the fractional loss in gross world/regional output due to climate change

ΔT represents temperature rise relative to a pre-industrial level

β is set at 2 or 3 in all models surveyed

α is a calibration constant

3. *Aggregate output*

$$Q = [A(K^{\alpha} \cdot L^{(1-\alpha)})^{\rho} + B(AEEI \cdot E^{\beta} \cdot N^{(1-\beta)})^{\rho}]^{1/\rho}$$

where Q = output excluding energy sector

K = capital input

L = labour input

E = electric energy input

N = non-electric energy input

A, B = scale factors

AEEI = autonomous energy efficiency improvements

α = elasticity of substitution between capital and labour

β = elasticity of substitution between electric and non-electric energy

ρ = (ESUB - 1)/ESUB

ESUB = elasticity of substitution

Note that this is the precise functional form used in CETA and MERGE. The Cobb-Douglas functional form used in RICE, DICE, and DICAFE is a special case of the above form obtained when $\rho \rightarrow 0$, and $B = 0$.

Table B.5: Global CO_2 Emissions and Concentrations in 2100 (base case results)

Model/Authors	Concentrations (ppmv)	Emissions (BTC per year)
RICE (Nordhaus & Yang, 1996)	1700 (BTC)	38
DICE (Nordhaus, 1994)	1500 (BTC)	25
DICAFE (Khanna & Chapman, 1996)	2650 (BTC)	68
MERGE (Manne, Mendelsohn, & Richels, 1995)	800	28
Wigley, Richels, & Edmonds (1996)	540 *(stabilized at 550 ppmv)* 650 *(stabilized at 750 ppmv)*	7 *(peak at 10-12 BTC in 2025)* 12.5 *(peak at 14 BTC in 2075)*
CETA (Peck & Teisberg, 1992 & 1995)	Not reported	40

Note: *The DICE, RICE, and DICAFE models do not report the concentration levels in terms of ppmv. Instead, the cumulative atmospheric levels of GHG emissions, after taking account of the natural decay processes and transfer to the deep ocean, are reported.*

APPENDIX C.

TABLE C.1 ALTERNATIVE EQUITY CRITERIA FOR GLOBAL WARMING POLICY

Criterion	Basic Definition	General Operational Rule	Operational Rule for CO_2 Permits
Horizontal	All nations should be treated equally	Equalize net welfare change across nations (net cost of abatement as proportion of GDP equal for each nation)[a]	Distribute permits to equalize net welfare change (net cost of abatement as proportion of GDP equal for each nation)[a]
Vertical	Welfare changes should vary inversely with national economic well-being	Progressively share net welfare change across nations (net cost proportions inversely correlated with per capita GDP)[a]	Progressively distribute permits (net cost proportions inversely correlated with per capita GDP)[a]
Ability to Pay	Mitigation costs should vary inversely with national economic well-being	Equalize abatement costs across nations (gross cost of abatement as proportion of GDP equal for each nation)[b]	Distribute permits to equalize abatement costs (gross cost of abatement as proportion of GDP equal for each nation)[b]
Sovereignty	All nations have an equal right to pollute and to be protected from pollution	Cut back emissions in a proportional manner across all nations	Distribute permits in proportion to emissions
Egalitarian	All people have an equal right to pollute and to be protected from pollution	Cut back emissions in proportion to population	Distribute permits in proportion to population
Market Justice	The market is fair	Make greater use of markets	Distribute permits to highest bidder
Consensus	The international negotiation process is fair	Seek a political solution promoting stability	Distribute permits in a manner that satisfies the (power weighted) majority of nations
Compensation	No nation should be made worse off	Compensate net losing nations	Distribute permits so no nation suffers a net loss of welfare
Rawls' Maximin	The welfare of the worst-off nations should be maximized	Maximize the net benefit to the poorest nations	Distribute largest proportion of net welfare change to poorest nations
Environmental	The environment should receive preferential treatment	Cut back emissions to maximize environmental values	Limit permits associated with vulnerable ecosystems (e.g., forests)

[a]Net cost equal to the sum of mitigation benefits - abatement costs + permit sales revenues - permit purchase costs.
[b]Gross cost refers to abatement cost only.

APPENDIX D.

Regional Delineations

1. UNITED STATES

2. CANADA

3. CENTRAL AMERICA AND CARIBBEAN
   - Bahamas
   - Belize
   - Costa Rica
   - Cuba
   - Dominican Republic
   - El Salvador
   - Guatemala
   - Haiti
   - Honduras
   - Jamaica
   - Mexico
   - Nicaragua
   - Panama
   - Trinidad & Tobago

4. SOUTH AMERICA
   - Argentina
   - Bolivia
   - Brazil
   - Chile
   - Columbia
   - Ecuador
   - French Guiana
   - Guyana
   - Paraguay
   - Peru
   - Suriname
   - Uruguay
   - Venezuela

5. WESTERN EUROPE
   - Andorra
   - Austria
   - Belgium
   - Denmark
   - Finland
   - France
   - Germany
   - Greece
   - Greenland
   - Iceland
   - Ireland
   - Italy
   - Liechtenstein
   - Luxembourg
   - Malta
   - Netherlands
   - Norway
   - Portugal
   - Spain
   - Sweden
   - Switzerland
   - United Kingdom

6. FORMER SOVIET UNION

7. EASTERN EUROPE
   - Albania
   - Bulgaria
   - Czechoslovakia (former)
   - Hungary
   - Poland
   - Romania
   - Yugoslavia (former)

8. OCEANIA
   - Australia
   - Fiji
   - New Caledonia
   - New Zealand

9. INDIA

10. CHINA

11. JAPAN

12. INDONESIA

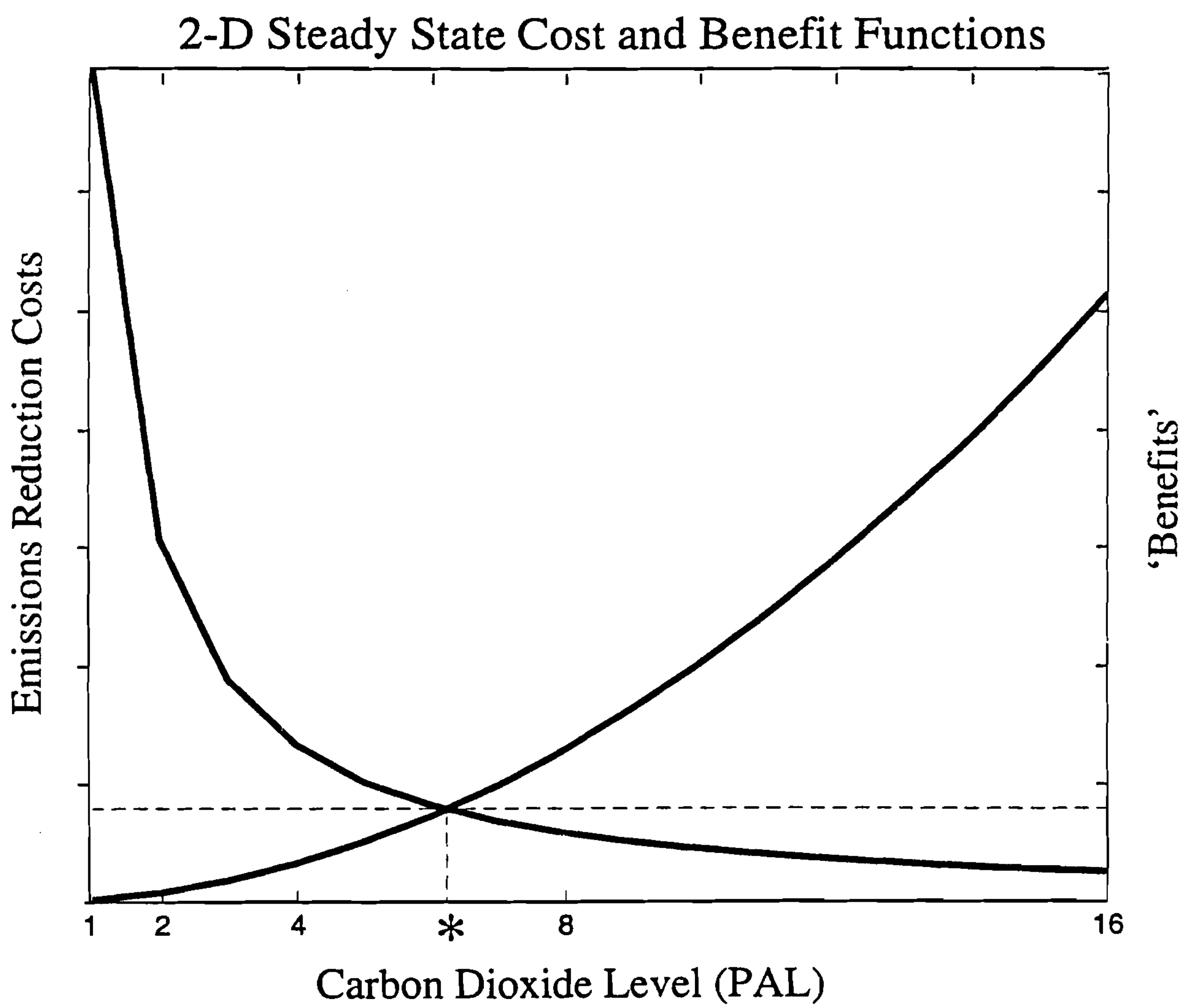
13. SOUTHEAST ASIA (OTHER)
   - Bangladesh
   - Burma
   - Kampuchea
   - Korea, North
   - Korea, South
   - Laos
   - Malaysia
   - Mongolia
   - Nepal
   - Pakistan
   - Papua New Guinea
   - Philippines
   - Sri Lanka
   - Taiwan
   - Thailand
   - Viet Nam

14. SOUTHWESTERN ASIA, MIDDLE EAST, AND NORTHERN AFRICA
   - Afghanistan
   - Algeria
   - Cyprus
   - Egypt
   - Ethiopia
   - Iran
   - Iraq
   - Israel
   - Jordan
   - Kuwait
   - Lebanon
   - Liberia
   - Libya
   - Morocco
   - Oman
   - Qatar
   - Saudi Arabia
   - Syria
   - Tunisia
   - Turkey
   - United Arab Emirates
   - Yemen

15. CENTRAL AND SOUTHERN AFRICA

Angola
Benin
Botswana
Burkina Faso
Burundi
Cameroon
Central African Rep.
Chad
Congo
Djibouti
Equatorial Guinea
Gabon
Gambia
Ghana
Guinea
Guinea-Bissau
Ivory Coast
Kenya
Lesotho
Madagascar
Malawi
Mali
Mauritania
Mauritius
Mozambique
Niger
Nigeria
Rwanda
Senegal
Sierra Leone
Somalia
South Africa
Sudan
Tanzania
Togo
Uganda
Western Sahara
Zaire
Zambia
Zimbabwe

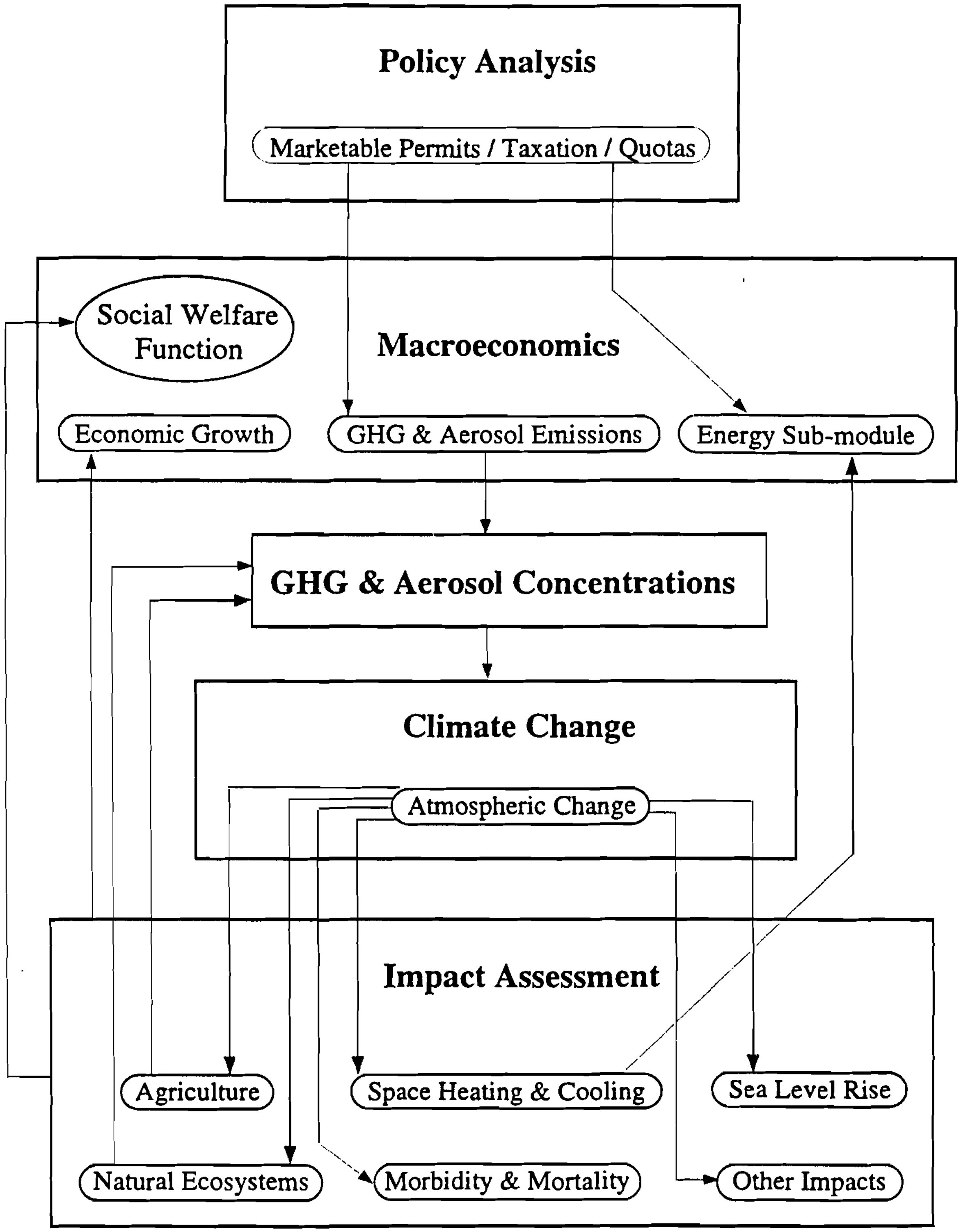
Figure 1.



* = optimal steady state carbon dioxide level

(PAL is the pre-industrial atmospheric level)

Figure 2.



Policy Analysis
Marketable Permits / Taxation / Quotas
Social Welfare Function
Macroeconomics
Economic Growth
GHG & Aerosol Emissions
Energy Sub-module
GHG & Aerosol Concentrations
Climate Change
Atmospheric Change
Impact Assessment
Agriculture
Space Heating & Cooling
Sea Level Rise
Natural Ecosystems
Morbidity & Mortality
Other Impacts

Figure 3.

The Nordhaus DICE model

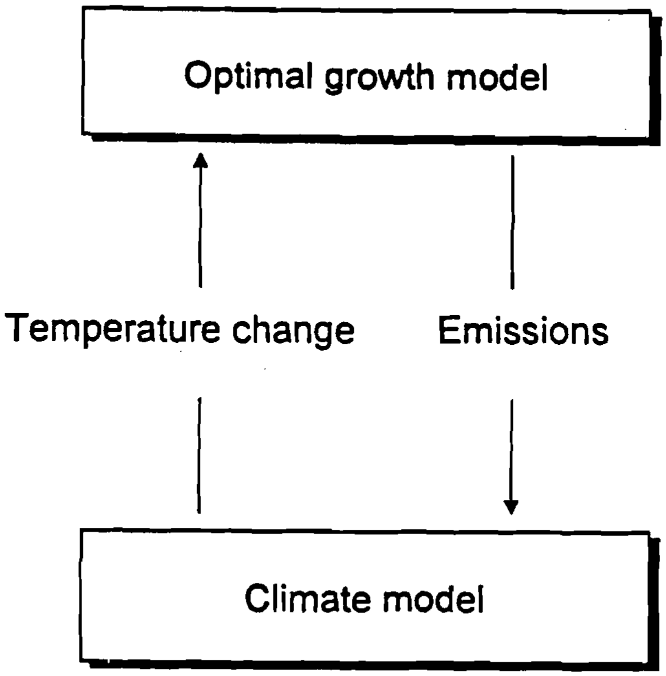


Figure 4.

The Cornell-PSU framework

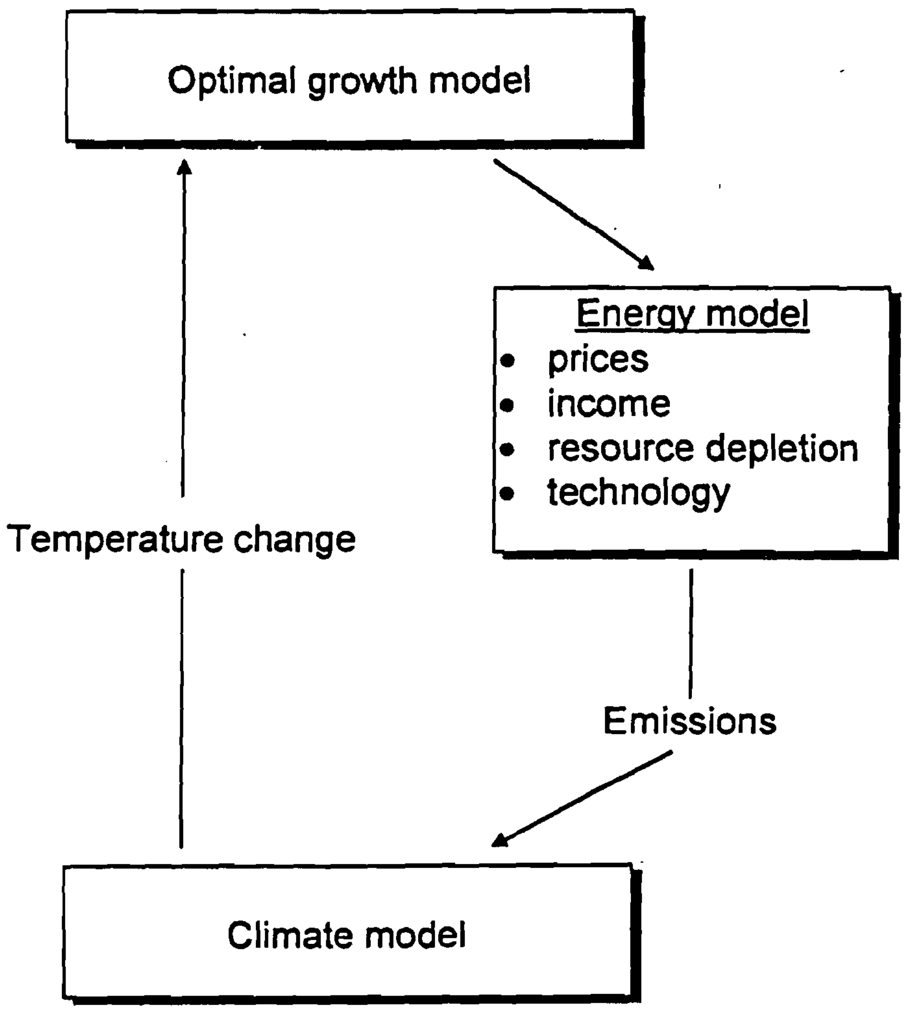


Figure 5.

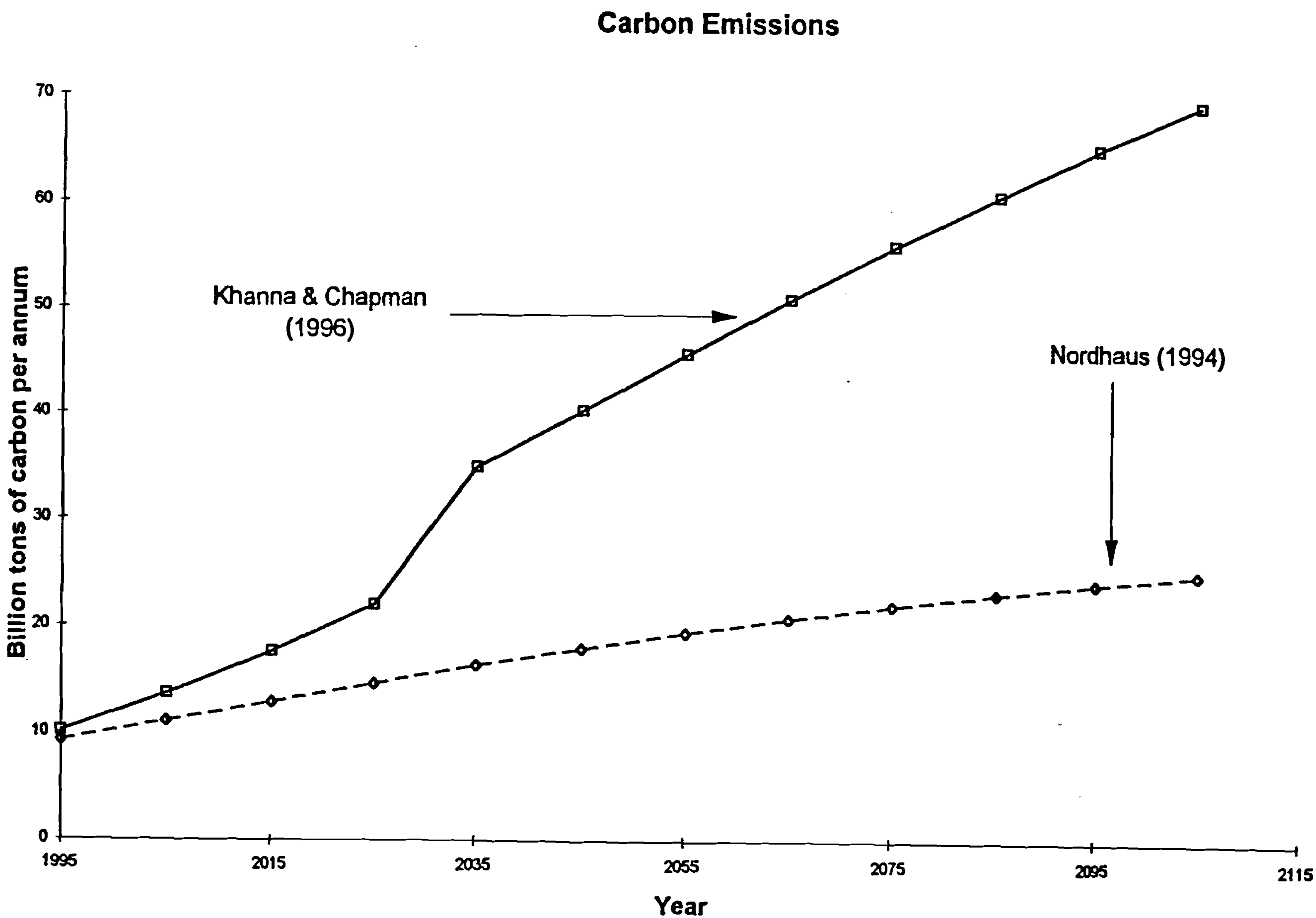

Carbon Emissions
Billion tons of carbon per annum
70
60
50
40
30
20
10
0
Khanna & Chapman
(1996)
Nordhaus (1994)
1995
2015
2035
2055
2075
2095
2115
Year

Figure 6.

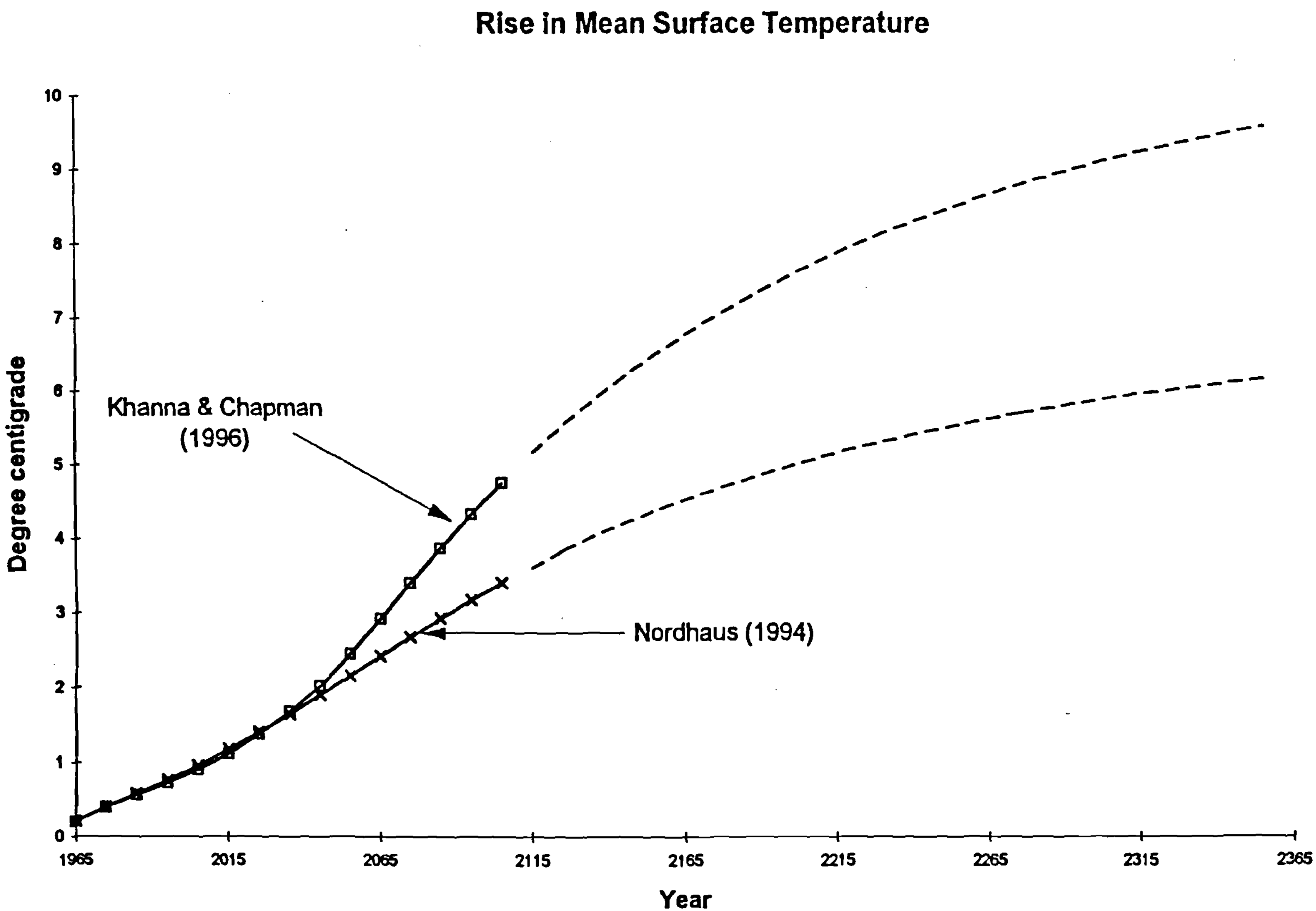
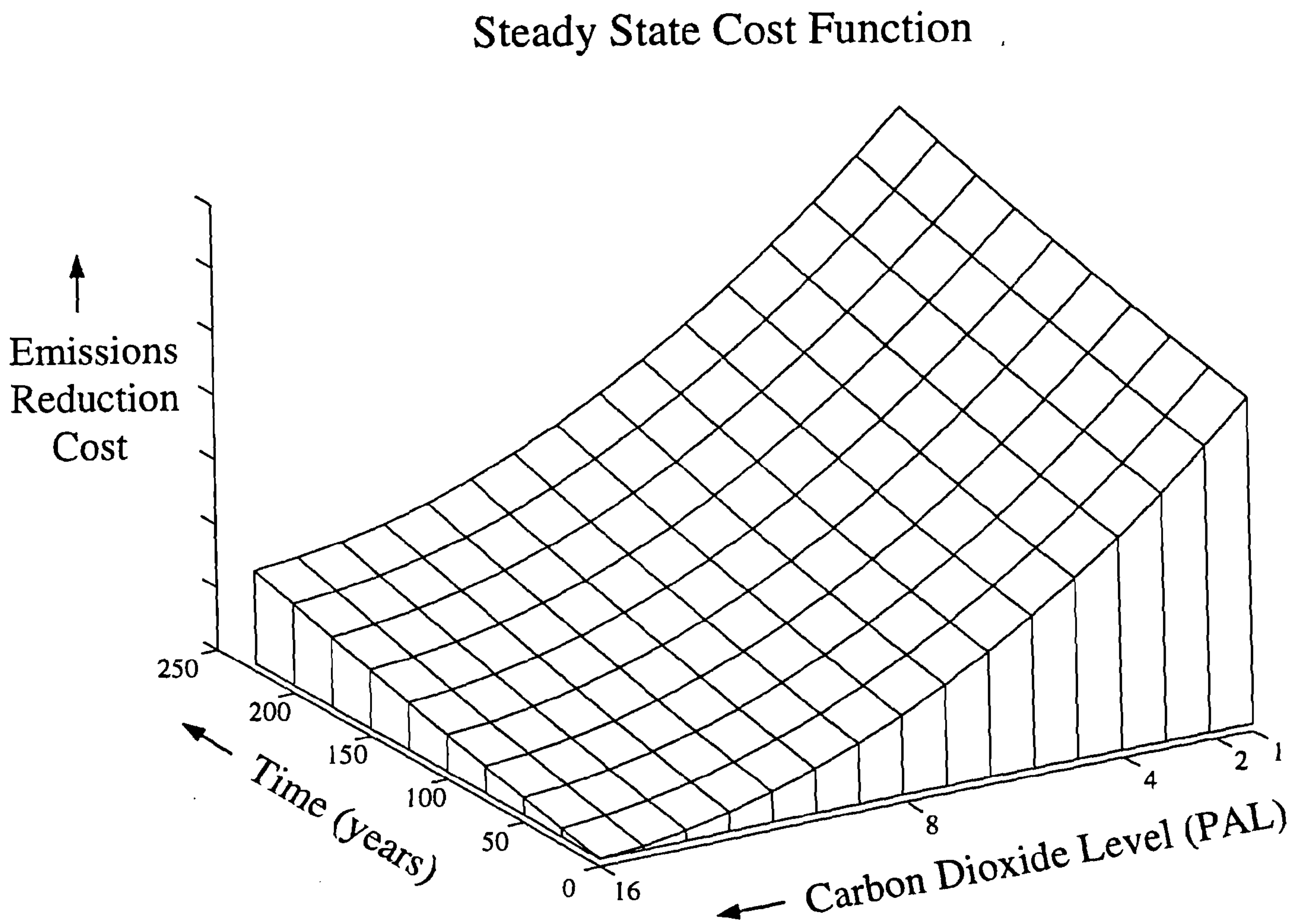

Rise in Mean Surface Temperature
Degree centigrade
Year
0
1
2
3
4
5
6
7
8
9
10
1965
2015
2065
2115
2165
2215
2265
2315
2365
Khanna & Chapman (1996)
Nordhaus (1994)

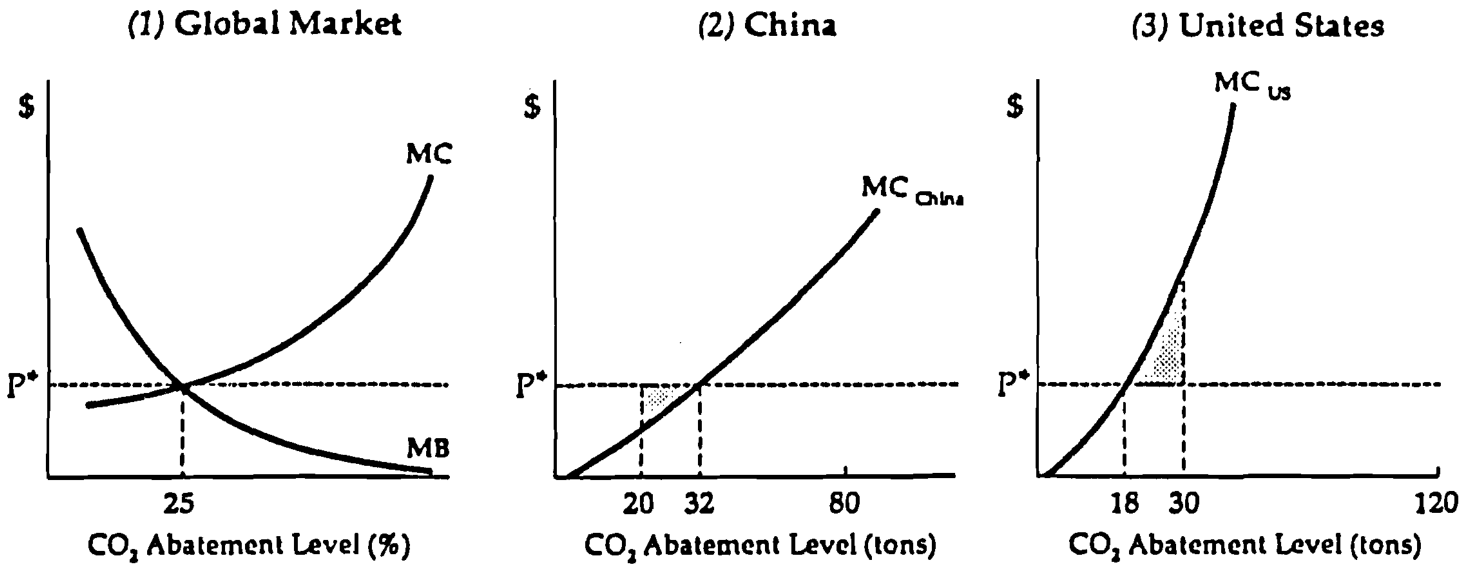
Figure 7.



Steady State Cost Function
Emissions
Reduction
Cost
250
200
150
100
50
0
Time (years)
16
8
4
2
1
Carbon Dioxide Level (PAL)

Figure 8.

Globally Efficient CO_2 Abatement



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