Modeling the Impacts of Climate Change: Elements of a Research Agenda

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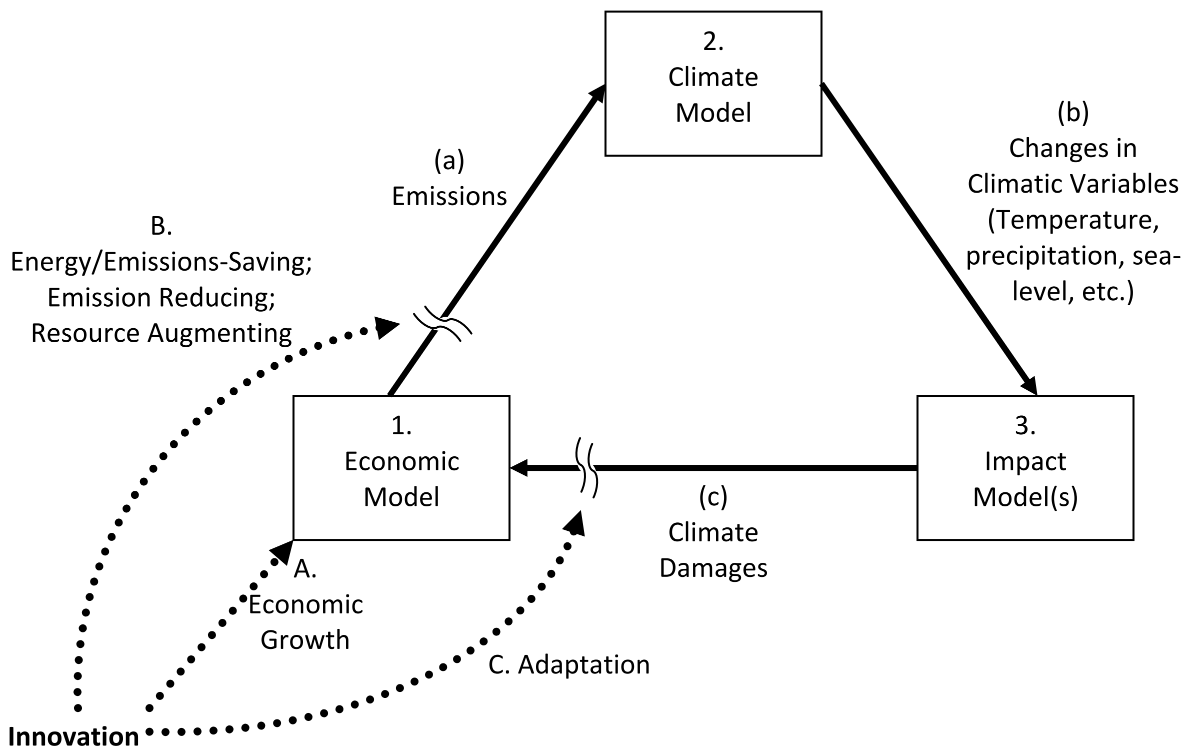
Abstract

1 Introduction: What is an IAM?

As illustrated in Figure 1, an integrated assessment model (IAM) of climate change is typically constructed from three interlinked sub-models, an economic model (1), a climate model (2) and an impacts model (3). It is logical to begin with the economic sub-model, which is responsible for generating time-paths of global emissions of greenhouse gases (GHGs—principally carbon dioxide, CO_2) (a). These serve as inputs to the climate sub-model, which uses them to project changes in the magnitude of meteorological variables such as temperature, precipitation or sea level rise (b). Finally, the changes in climate parameters are translated into projections of global- or regional-scale economic losses by an impacts sub-model, whose primary role is to capture the feedback effect of dangerous near-term anthropogenic interference with the climate on economic activity over the long-term future (c).

Innovation is a key modulator of the clockwise circulation of the feedback loop in the figure. Improvements in the productivity of labor induce more rapid growth and increase the demand for fossil energy resources, which has a first-order amplifying effect on emissions (A). Energy- or emissions-saving technological progress tends to depress the emission intensity of the economy, slowing the rate of increase in fossil fuel use; conversely, productivity improvements in energy resource extraction lower the price of fossil fuels and induce substitution toward them, increasing emissions (B). Lastly, we can imagine that there may be innovations that boost the effectiveness of defensive expenditures undertaken in response to the threat of climate damages, or investments in creating new knowledge that enables humankind to mitigate some climate damages (C). This last category is the most speculative, as impacts will manifest themselves several decades in the future, when the state of technology is likely to be quite different from today.

Figure 1: Integrated Assessment of Climate Change and the Effects of Innovation



2 Land of Cockaigne: An IAM with Regional, Sectoral and Climate Impact Detail

Imagine that there were relatively few constraints to either our computational resources or our ability to foresee the impacts of climate change. In such a world, what would an IAM look like? We could then specify a RICE- or AD-WITCH-type IAM that resolved (a) the detailed sectoral structure of production in various regions, (b) the effects of climate impacts on the productivity of those sectors, (c) the manner in which different impact endpoints combined to generate the resultant productivity effects, and (d) the response of the full range of impacts to changes in climatic variables at regional scale.

Let us write down such a model, and exploit its structure to assess the implications for the social cost of carbon. Define the following nomenclature:

Set indexes:	
$t = \{0, \ldots, \mathscr{T}\}$	Time periods
$\ell = \{1, \ldots, \mathscr{L}\}$	World regions
$j = \{1, \ldots, \mathscr{N}\}$	Industry sectors
$m = \{1, \ldots, \mathscr{M}\}$	Meteorological characteristics
$f = \{1, \ldots, \mathscr{F}\}$	Climate impact endpoints
Control variables:	
$q^E_{j,\ell,t}$	Sectoral energy input
$q^K_{j,\ell,t}$	Sectoral capital input
$Q^C_{\ell,t}$	Aggregate consumption
$Q^I_{\ell,t}$	Aggregate jelly capital investment
$a^f_{j,\ell,t}$	Region-, sector- and impact-specific averting expenditure
$v^f_{j,\ell,t}$	Region-, sector- and impact-specific adaptation investment
Economic state variables:	
$\mathscr{W}$	Welfare (model objective)
$q^Y_{j,\ell,t}$	Net sectoral product
$Q^Y_{\ell,t}$	Aggregate net regional product
$Q^E_{\ell,t}$	aggregate regional energy use
P^E_t	Global marginal energy resource extraction cost

$Q^K_{\ell,t}$	Stock of aggregate jelly capital
$x^f_{j,\ell,t}$	Stock of region-, sector- and impact-specific adaptation capital
Environmental state variables:	
G_t	Global stock of atmospheric GHGs
$M^m_{\ell,t}$	Region-specific meteorological variables
$z^f_{j,\ell,t}$	Region-, sector-, and impact-specific endpoint indexes
$\Lambda_{j,\ell,t}$	Region- and sector-specific damage induced productivity losses
Functional relationships:	
Ξ	Global intertemporal welfare
U_ℓ	Regional intratemporal utility
Φ_ℓ	Regional aggregate production functions
$\psi_{j,\ell}$	Sectoral production functions
Θ	Global energy supply function
$\mathcal{E}$	Global atmospheric GHG accumulation
Υ^m_ℓ	Regional climate response functions
$\zeta^f_{j,\ell}$	Regional and sectoral climate impacts functions
$\lambda_{j,\ell}$	Regional and sectoral damage functions

1. Economic Sub-Model

Objective:

$$\max_{Q^C_{\ell,t}, q^E_{j,\ell,t}, q^K_{j,\ell,t}} \mathscr{W} = \sum_{t=0}^{T} \beta^t \Xi \left[U_1 \left[Q^C_{1,t} \right], \ldots, U_{\mathscr{L}} \left[Q^C_{\mathscr{L},t} \right] \right] \tag{1a}$$

Aggregate net regional product:

$$Q^Y_{\ell,t} = \Phi_\ell \left[q^Y_{1,\ell,t}, \ldots, q^Y_{\mathscr{N},\ell,t} \right] \tag{1b}$$

Sectoral net regional product = Climate loss factor × Sectoral gross regional product, produced from energy and capital:

$$q^Y_{j,\ell,t} = \Lambda_{j,\ell,t} \cdot \psi_{j,\ell} \left[q^E_{j,\ell,t}, q^K_{j,\ell,t} \right] \tag{1c}$$

Intraregional and intratemporal market clearance for energy:

$$\sum_{j=1}^{\mathscr{N}} q^E_{j,\ell,t} = Q^E_{\ell,t} \tag{1d}$$

Intraregional and intratemporal market clearance for jelly capital:

$$\sum_{j=1}^{\mathscr{N}} q^K_{j,\ell,t} = Q^K_{\ell,t} \tag{1e}$$

Aggregate regional absorption constraint:

$$Q^C_{\ell,t} = Q^Y_{\ell,t} - Q^I_{\ell,t} - P^E_t Q^E_{\ell,t} - \sum_{f=1}^{\mathscr{F}} \sum_{j=1}^{\mathscr{N}} \left(a^f_{j,\ell,t} + v^f_{j,\ell,t} \right) \tag{1f}$$

Global energy trade and marginal resource extraction cost:

$$P^E_t = \Theta \left[\sum_{\ell=1}^{\mathscr{L}} \sum_{s=0}^{t} Q^E_{\ell,s} \right] \tag{1g}$$

Regional jelly capital accumulation:

$$Q^K_{\ell,t+1} = Q^I_{\ell,t} + (1 - \vartheta^K) Q^K_{\ell,t} \tag{1h}$$

Accumulation of impact-, sector- and region-specific adaptation capital:

$$x^f_{j,\ell,t+1} = v^f_{j,\ell,t} + (1 - \vartheta^f) x^f_{j,\ell,t} \tag{1i}$$

2. Climate Sub-Model

Global atmospheric GHG accumulation:

$$G_{t+1} = \mathcal{E} \left[\sum_{\ell} Q^E_{\ell,t}, G_t \right] \tag{2a}$$

Regional meteorological effects of global atmospheric GHG concentration:

$$M^m_{\ell,t} = \Upsilon^m_{\ell} \left[G_t \right] \tag{2b}$$

3. Impacts Sub-Model

Physical climate impacts by type, sector and region:

$$z^f_{j,\ell,t} = \zeta^f_{j,\ell} \left[M^1_{1,0}, \ldots, M^{\mathscr{M}}_{1,0}; \ldots; M^1_{\mathscr{L},t}, \ldots, M^{\mathscr{M}}_{\mathscr{L},t} \right] \tag{3a}$$

Climate damages:

$$\Lambda_{j,\ell,t} = \lambda_{j,\ell} \left[z^1_{j,\ell,t}, \ldots, z^{\mathscr{F}}_{j,\ell,t}; a^1_{j,\ell,t}, \ldots, a^{\mathscr{F}}_{j,\ell,t}; x^1_{j,\ell,t}, \ldots, x^{\mathscr{F}}_{j,\ell,t} \right] \tag{3b}$$

From the point of view of period $t^\star$, the condition for optimal extraction of carbon-energy is:

$$
\begin{aligned}
\frac{\partial \mathscr{W}}{\partial Q^E_{\ell^\star,t^\star}} \Bigg/ \frac{\partial \mathscr{W}}{\partial Q^C_{\ell^\star,t^\star}} = & \underbrace{\sum_{j=1}^{\mathscr{N}} \left(\frac{\partial \phi_{\ell^\star}}{\partial q^Y_{j,\ell^\star,t^\star}} \frac{\partial \psi_{j,\ell^\star}}{\partial q^E_{j,\ell^\star,t^\star}} \frac{\partial q^E_{j,\ell^\star,t^\star}}{\partial Q^E_{\ell^\star,t^\star}} \right)}_{\text{I. Current marginal benefit}} - \underbrace{P^E_{t^\star}}_{\substack{\text{II. Current marginal} \\ \text{extraction cost}}} \\
& - \underbrace{\sum_{t=t^\star}^{T} \beta^{t-t^\star} \sum_{\ell=1}^{\mathscr{L}} \left(\frac{\partial \Xi}{\partial U_\ell} \frac{\partial U_\ell}{\partial Q^C_{\ell,t}} \frac{\partial \Theta}{\partial Q^E_{\ell^\star,t^\star}} Q^E_{\ell,t} \right) \Bigg/ \left(\frac{\partial \Xi}{\partial U_{\ell^\star}} \frac{\partial U_{\ell^\star}}{\partial Q^C_{\ell^\star,t^\star}} \right)}_{\text{III. Resource stock effect of contemporaneous energy use}} \\
& \underbrace{\begin{aligned} + \sum_{t=t^\star+1}^{T} \beta^{t-t^\star} \frac{\partial \mathcal{E}}{\partial Q^E_{\ell^\star,t^\star}} \Bigg/ \left(\frac{\partial \Xi}{\partial U_{\ell^\star}} \frac{\partial U_{\ell^\star}}{\partial Q^C_{\ell^\star,t^\star}} \right) \\ \times \sum_{\ell=1}^{\mathscr{L}} \left\langle \frac{\partial \Xi}{\partial U_\ell} \frac{\partial U_\ell}{\partial Q^C_{\ell,t}} \sum_{j=1}^{\mathscr{N}} \left\{ \frac{\partial \phi_\ell}{\partial q^Y_{j,\ell,t}} \psi_{j,\ell,t} \sum_{f=1}^{\mathscr{F}} \left[\frac{\partial \lambda_{j,\ell}}{\partial z^f_{j,\ell,t}} \sum_{m=1}^{\mathscr{M}} \left(\frac{\partial \zeta^f_{j,\ell}}{\partial M^m_{\ell,t}} \frac{\partial \Upsilon^m_\ell}{\partial G_t} \right) \right] \right\} \right\rangle \end{aligned}}_{\text{IV. Present value of future marginal climate damage (N.B. } \partial q^Y / \partial \Lambda < 0 \text{ in general)}} \\
& = 0 \qquad (4)
\end{aligned}
$$

The "social cost of carbon" in this expression is given by the combination of terms (II) + (III) - (IV). Our interest is in (IV), the marginal external cost of carbon-energy consumption, which, because it emanates from a globally well-mixed pollutant, is independent of the location in which the energy is consumed.

It is now clear to see how fundamental gaps in our understanding the render the "land of cockaigne" unattainable. The difficulty in computing the social cost of carbon stems from the terms in curly braces. Carbon-cycle modeling is sufficiently advanced to enable us to predict with a fair degree of confidence the effect of the marginal ton of carbon on the time-path of future atmospheric GHGs ($\partial \mathcal{E} / \partial Q^E$). Likewise, the IPCC AR4 notes global climate models' substantially improved ability to capture the future trajectory of consequent changes in temperature, precipitation, ice/snow cover and sea levels at regional scales ($\partial \Upsilon^m_\ell / \partial G$). But the weak links in the causal chain between climate change and economic damages continue to be the cardinality and magnitude of the vectors of physical impact endpoints as a function of climatic variables in each region out into the future

$(\partial \zeta^f_{j,\ell} / \partial M^m_\ell)$, and—to a lesser extent—the manner in which these endpoints translate into shocks to the productivity of economic sectors $(\partial \lambda_{j,\ell} / \partial z^f_{j,\ell})$.

3 A Critical Review of the State of Modeling Practice

To put the key issues in sharp relief, it is useful to consider how implementing the disaggregated IAM might improve upon the current state of integrated assessment practice. RICE-type IAMs represent the productivity losses incurred by climate change impacts through variants of Nordhaus' aggregate damage function, which specifies the reduction in gross regional product as a function of global mean temperature. This approach effectively collapses M^m_ℓ to a scalar quantity in each time period. Moreover, as reviewed by NRC (2010), it then benchmarks the magnitude of various impacts and the associated economic losses for a reference level of global mean temperature change, before making assumptions about how these costs are likely to scale with income, and finally expressing damage as a temperature-dependent fraction of regions' gross output. Therefore, the details of climatic variables' influence on impact endpoints in (3a), and of the latter's effects on economic sectors in (3b), only affect the calibration of the damage function. From that point on they are entirely subsumed within the function's elasticity with respect to global temperature change, and, in RICE-2010, sea level rise. The damage function therefore collapses (3a) into (3b), dealing only with changes in aggregate global climatic variables, skipping over impacts as state variables and implicitly aggregating over sectors to express damages purely on an aggregate regional basis.

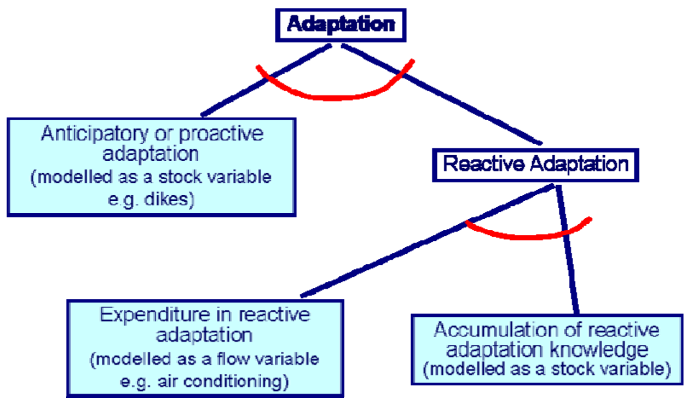
A similar situation obtains with adaptation. A case in point is the AD-WITCH model, a variant of Nordhaus' RICE simulation which modifies the damage function by introducing stock and flow adaptation expenditures which attenuate aggregate regional productivity losses due to climate change. Formally, using $\widetilde{Q}^Y$ to denote gross regional product, net regional product is given by

$$Q^{Y}_{\ell,t} = \frac{1 + ADAPT_{\ell,t}}{1 + ADAPT_{\ell,t} + CCD_{\ell,t}}\, \widetilde{Q}^{Y}_{\ell,t} \tag{5}$$

where CCD is the regional climate damage function and $ADAPT$ is an index of adaptation's effectiveness. The variable $ADAPT$ is the output of a nested constant elasticity of substitution (CES) production function which combines inputs of contemporaneous averting expenditures with adaptation capital and adaptation knowledge according to Figure 2. The key consequence is that adaptation is able to directly influence the dynamic path of the economy, instead of being implicit in the curvature of the damage function, as with the RICE model. However, eq. (5)'s assumption that the effects of $ADAPT$ and CCD are multiplicative seems very strong in light of the fact that the damage function already explicitly incorporates the influence of adaptation through the studies on which it is benchmarked—but only at the calibration point, not over the full range of its curvature. A prime example is Nordhaus and Boyer's (2000) use of Yohe and Schlesinger's (1998) results on the impact of sea level rise, which optimally balance the costs of abandonment and coastal defenses. The implication is that because defensive expenditures are likely to be closely associated with the magnitudes of climate impacts of various kinds within individual sectors, one should not think of aggregate adaptation expenditure as independent of future changes in the sectoral composition of output.

By dispensing with the aggregate damage function, our land of cockaigne IAM explicitly captures the dynamic evolution of impact endpoints' response to changes in climatic variables, the magnitude and intersectoral distribution of the follow-on productivity effects, and the optimal intersectoral adjustments these induce, all at regional scales. An adaptation response may therefore be modeled more precisely as averting expenditure that mitigates the sectoral and regional productivity loss associated with a particular category of climate impact. In other words, stock and flow adaptation reduces the impact

Figure 2: The AD-WITCH Adaptation Production Function (Bosello, Carraro and De Cian, 2010)



elasticity of sectoral productivity shocks. Of course, the problem that besets this approach is that, except for a very few combinations of impacts, sectors and regions, the relevant elasticities are unknown.

But the good news is that this is one area in which research is proceeding apace. There are a growing number of CGE modeling studies of climate impacts (e.g., ICES) which elucidate the magnitude of both sectoral and regional damages and producers' and consumers' adjustment responses. The focus of such studies is typically a single impact category (say, $f^\star$), whose initial economic effects are computed using natural science or engineering modeling or statistical analyses. The results are often expressed as a vector of shocks to exposed sectors and regions, which are then imposed as exogenous productivity declines on the CGE models' cost functions. In the context of the IAM in section 2, this procedure is equivalent to first specifying an exogenous ex-ante effect of a particular impact $\overline{\partial \lambda_{j,\ell} / \partial z^{f^\star}_{j,\ell}}$, before using the CGE model to compute the ex-post web of intersectoral adjustments and the consequences for sectoral output, and regions' aggregate net product and welfare:

$$\frac{\partial U_\ell}{\partial Q^C_{\ell,t}} \sum_{j=1}^{\mathcal{N}} \left(\frac{\partial \phi_\ell}{\partial q^Y_{j,\ell,t}} \psi_{j,\ell,t} \frac{\overline{\partial \lambda_{j,\ell}}}{\partial z^{f^\star}_{j,\ell}} \right).$$

This line of inquiry has the potential to yield two critical insights. The first is quantification of the elasticity of the economy's response to variations in the magnitude and interregional/intersectoral distribution of particular types of impact, which has been the type of investigation pursued thus far. But second—and arguably more important—is comparative analysis of economic responses *across* different impact categories for the purpose of establishing their relative overall economic effect, conditional on our limited knowledge of their relative likelihood of occurrence, and intensity. The results could at the very least guide the allocation of effort in investigating the thorny question of how different impacts are likely to respond to climatic forcings at the regional scale, $\partial\zeta^{f}_{j,\ell}/\partial M^{m}_{\ell}$.