Modeling Climate Change Adaptation: Challenges, Recent Developments and Future Directions

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Abstract

This paper offers a critical review of modeling practice in the field of integrated assessment of climate change and ways forward. Past efforts in integrated assessment have concentrated on developing baseline trajectories of emissions and mitigation scenario analyses. A key missing component in IAMs is the representation of climate impacts and adaptation responses. Through the examination of conceptual, theoretical and empirical frameworks for the analysis of climate impacts and adaptation, we identify five characteristics of an ideal IAM: regional and sectoral detail for impacts and adaptation strategies; distinct representation of the three types of adaptation—adaptation through market adjustments, protective/defensive expenditures, and adaptive/coping expenditures; intertemporal decision making under uncertainty; induced innovation in adaptation-related technologies; and connection with empirical work on impacts and adaptation. Our review of existing IAMs finds that most models are severely lacking in most of these modeling features.

I. Introduction

The vast majority of integrated assessments of climate change have concentrated on developing baseline emissions scenarios and analyzing the economic consequences of emission mitigation policies. A serious shortcoming of many existing integrated assessment models (IAMs) is the omission of climate impacts and the economic responses thereto, in particular investments related to climate change adaptation. This state of affairs originates in our limited understanding of how anthropogenic radiative forcing induces changes in temperature, precipitation and various other biophysical impact endpoints at regional scales, and what the concomitant damages to the various economic sectors within these regions might be. The good news is that this situation is slowly improving, with several advances made over the past decade to introduce impacts and adaptation into IAMs. The purpose of this paper is to provide a survey of these approaches and identify promising directions for future research in this domain.

The paper is organized as follows. Section II provides the motivation for the paper, discussing the special challenges that attend modeling the processes of adapting to climate change. In Section III we present conceptual, theoretical and empirical frameworks for understanding and analyzing climate impacts and adaptation, and highlight the disconnects between recent econometric research and modeling practice using the device of a stylized IAM. Section IV employs the insights thus generated to critically survey IAM studies of impacts and adaptation. Section V concludes by offering new directions for future research.

II. Confronting the Challenges of Modeling Adaptation

It is instructive to begin by addressing two questions: what are the unique features of climate adaptation, and what special challenges do they pose to integrated assessment modeling?

The fundamental premise of this paper is that the biophysical impacts of climate change will be spatially heterogenous, resulting in shocks to natural and human systems that differ in character and magnitude across regions.[1] Climate damages are also likely to be sector-specific, with particular categories of economic activity (e.g., agriculture, coastal settlements) being more severely impacted than others. Furthermore, because adaptation strategies tend to involve the targeting of defensive expenditures to these exposed sectors—and more intensively in regions where the latter are expected to be especially vulnerable—the adaptation process is likely to be regionally and sectorally differentiated as well. An ideal IAM would therefore contain sufficient regional and sectoral detail to resolve the variation in climate impacts and responses, or at least consistently aggregate these fine-scale artifacts up to a coarser representation.

A second key point is that adaptation comes in different forms: passive general market reactions—e.g., changing heating and cooling expenditures or shifts in choice of tourism destinations; specific reactive adaptation investments—e.g., treatment of vector-borne disease; and specific proactive adaptation investments—the hardening of vulnerable infrastructure, development of early warning systems, and expansion of capacity for climate-related disaster preparedness and response. Virtually all IAMs already embody the capability to simulate passive adaptation as the endogenous market responses to climate-induced changes in prices; for example, increases in electric generation in response to higher demand for cooling due to summer heat waves; or reductions in rain-fed crop production induced by declining productivity of land due to lower precipitation. In such cases all that is necessary to simulate adaptation is to introduce a region-by-sector array of climate impacts into existing IAMs. Although the process

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[1] Geographic variation in current climates translates into different initial conditions from which regions' climates will change. The areas that are likely to experience the largest changes are those that are already near the boundaries between climatic regimes—whose locus will shift as a consequence of global warming. With moderate climate change, areas which are more distant from these boundaries will be less affected by these spatial regime shifts, and will likely experience impacts of a much smaller magnitude.

of specifying impacts as shocks to the economy can be quite involved (cf. section III), modeling reactive adaptation is comparatively straightforward, which explains why it has been the focus of modeling studies over the past decade. But the corollary is that the extraordinarily difficulty of representing the effects of specific investments with any precision has proven a high barrier to introducing them into IAMs.

Thirdly, IAMs still have great difficulty in simulating proactive measures such as coastal protection without an explicit representation of the inducement of current investments by expected future climate damages. Unlike climate mitigation, where actions to abate greenhouse gases result in contemporaneous emission reductions, proactive adaptation investments are designed to protect against future impacts whose timing and magnitude are far from certain. Adaptation investments are inherently intertemporal, which implies that if IAMs are to have any chance of correctly simulating the trajectory of investment, they need to be able to capture the tradeoff between future damages and the mitigating influence of current defensive expenditures. Furthermore, the fact that economic actors' investment decisions are conditional on their expectations of impacts and their rate of time preference means that the former are inextricably linked to decisions to emit or abate greenhouse gases (GHGs) in the near term. To properly capture this web of influences we require models that allow for intertemporal decision-making under uncertainty.

Fourth, increases in the demand for adaptation will likely induce technological improvements in adaptation-related activities. An unresolved question is the degree to which such innovation differs significantly from mitigation-related technological change. Adaptation's comparative regional and sectoral specificity, coupled with the risk to public infrastructure from climate-related damage, may limit the market for new adaptation techniques and reduce the attractiveness of private R&D. Distinguishing between public and private innovation may be important. Note that this is more than a question of simply basic versus applied science, but driven by the nature of demand for the final product, much in the same way that the government finances most R&D for national defense. Thus, the model needs to be capable of distinguishing between private and public investments and include mechanisms of public revenue raising to fund these projects.

Lastly, despite a recent flurry of empirical research in the economics literature on impacts and adaptation, these investigations concentrate on a comparatively small set of regions and sectors, and moreover often tend to focus on the direct influence of climate parameters on economic outcomes, glossing over the fine details of climatic drivers or productivity consequences of specific biophysical impact endpoints. The upshot is a disconnect between empirical results and IAMs that necessitates heroic efforts to translate the former into representations of climate damages that are suitable for incorporation within the latter. Additionally, there are only a few empirical assessments of adaptation-related technological improvements that have been widely recognized to have significantly lowered the cost of responding to—or defending against—climate damages.[2] This deficit stems from a general lack of understanding of the ways in which this type of technological change proceeds, especially in so far as innovations are targeted toward improving the mitigation of specific impact endpoints. Thus, we need empirical research that not only covers a broader regional and sectoral scope, but is also subtly different in character, emphasizing elucidation of specific channels through which climate variables' economic impacts manifest themselves.

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[2] E.g., Landon-Lane et al (2011) conclude that banking system innovations post-1940 reduced the correlation between climate impacts on agricultural production and financial distress in the U.S. Midwest; Fishback et al (2011) find access to information to be a significant attenuator of temperature's influence on mortality, suggesting the beneficial effect of past U.S. public health camapaigns; and Hansen et al (2011) find that irrigation and dam infrastructure mitigated the impacts of drought or excessive precipitation.

III. Conceptual, Theoretical and Empirical Frameworks

In this section we examine three frameworks for the analysis of impacts and adaptation. We begin by offering a simple conceptual framework, before going on to illustrate its practical elaboration in the form of a stylized impact-centric IAM, the results of which highlight the crucial disconnect between empirical and model-based studies of climate impacts and adaptation.

A. A Bottom-Up Conceptual Model

Our conceptual model is illustrated schematically in Figure 1. It is deliberately simple, following the straightforward causal chain from GHGs to climate damages. Working downward from the top of the diagram, changes in atmospheric GHG concentrations as a result of human activities (i) drive changes in climate variables such as temperature and precipitation at the regional scale (ii). In turn, climatic changes give rise to impacts (iii) which influence the productivity of various sectors of the regional economies where the impacts occur (iv), giving rise to climate damages to the economy (v).

Less straightforward is adaptation induced by the threat, or the onset, of economic damages. The response of sectoral productivities to the character and magnitude of the initiating impacts is moderated by specific protective or defensive measures, which henceforth we refer to as Type II adaptations. A qualitatively different type of adaptation reduces the extent to which the productivity effects of impacts that do manifest themselves end up causing damage to economic sectors. We refer to specific investments of this kind as Type III adaptations. Lastly, for given levels of these specific adaptations (or no adaptation), the magnitude of the damages that do ultimately befall the economy also depend upon price changes and substitution responses across many markets. These passive general equilibrium adjustments may be thought of as a sort of adaptation in its own right, which we label Type I. The dashed lines in the figure are meant to emphasize that all three kinds of adaptation are themselves endogenous responses to expectations of economic damage wrought by climate impacts.

The fundamental insight of the diagram is that adaptation cannot be considered in isolation: it is inseparable from the overarching context of magnitude, and, crucially, the character of the climate impacts that generate the demand for adaptation responses in the first place. This suggests that quantification of the economic consequences of climate impacts rests critically on estimates of the responses of both key impact endpoints with respect to changes in climate variables at the regional scale (B) and sectoral productivity shocks with respect to these endpoints (C). Without these two key pieces of information, estimating the potential for adaptation to mitigate the economic damages from climate change will continue to be a matter of guesswork.

Formally, let the indexes m, j, ℓ, and i denote he sets of climatic characteristics, economic sectors, geographic locations and impact endpoints, respectively. Then, (B) can be thought of as a set of mathematical response functions, $\zeta^{i}_{j,\ell}$, which translate climate variables (M^{m}_{ℓ}) into biophysical impact endpoints ($b^{i}_{j,\ell}$). Likewise, (C) denotes a set of functions, $\lambda^{i}_{j,\ell}$, that translate impacts into shocks to productivity ($\Lambda_{j,\ell}$). The regional and sectoral specificity of impacts discussed earlier suggests that (B) and (C) are multidimensional response surfaces in the form of Table 1. This in turn implies that IAMs will only be able to fully exploit such disaggregate information if they incorporate a multi-sectoral representation of economic activity on which climate shocks can exert their economic impacts (e.g., via production functions denominated by region and sector, say $\psi_{j,\ell}$).

The key problem that besets the foregoing process-based approach is that current empirical research is unable to support parameterization of the detailed one-to-one relationships implied by Table 1. As we elaborate in section III.C below, econometric estimates of climate impacts' consequences cannot be easily translated into the form of Table 1, because of inadequate regional and sectoral coverage, and, frequently, the latent character of many individual biophysical endpoints of interest.

With regard to adaptation, Figure 1 demonstrates that measures to alleviate the effects of climate change can be classified in terms of investments designed to shield economic sectors from impacts (e.g., coastal protection infrastructure to defend against rising seas, or the development of drought- and heat-tolerant varieties of staple crops), and those intended to lessen the economic losses that arise once impacts actually exert their effects on the sectors in question (e.g., redundant or flexible production capacity, or investments in disaster preparedness, response and recovery). Although the reader might be tempted to interpret the former as proactive stock adaptation and the latter as reactive flow adaptation, this would not be strictly correct, as each category will in general include a mix of proactive and reactive measures. The essential difference between the two kinds of adaptation is the mechanism through which each exerts its moderating effect. Protective investments lessen sectors' exposure by reducing the marginal effects of climate impact endpoints on productivity changes ($\partial \zeta^{i}_{j,\ell} / \partial M^{m}_{\ell}$), while adaptive expenditures increase resilience by lowering the marginal effects of productivity shocks on economic losses ($\partial \lambda_{j,\ell} / \partial b^{i}_{j,\ell}$).

This distinction has potentially important implications for the allocation of adaptation investments under uncertainty. A fundamental prerequisite to limiting a particular sector's exposure to climate damage is an understanding of the influence of specific impact endpoints on its productivity. On the other hand, there are likely to be other types of expenditure that are "general purpose" in nature, in the sense that they lower the economy's costs of adjustment costs to shocks generally—regardless of the latter's origin in one or another endpoint, or whether they are even climate-related. If it is indeed the case that adaptive investments are more generic and fungible, while defensive investments are more impact- and sector-specific, then we would expect to see more of the adaptive and less of the defensive variety. But conjectures such as these can only be decided by empirical investigation. A potentially fruitful direction for future research is to improve our understanding of the distribution of investment by examining historical analogues from past changes in climate (see, e.g., Libecap and Steckel, 2011), and perhaps other natural hazards.

In terms of the implications for modeling practice, it is far more straightforward to separate adaptation investments into proactive and reactive components ($\pi^i_{j,\ell}$ and $\rho^i_{j,\ell}$), and model the accumulation of the former into a stock of adaptation capital ($a^i_{j,\ell}$). The challenge is then to specify the moderating effects of $\mathbf{a}$ and $\boldsymbol{\rho}$ on impacts and adverse productivity shocks wrought through their incorporation into region × sector impact and damage functions:

$$b^i_{j,\ell} = \zeta^i_{j,\ell}\left[\mathbf{M}_{j,\ell}; \rho^i_{j,\ell}, a^i_{j,\ell}\right] \tag{1a}$$

and

$$\Lambda_{j,\ell} = \lambda_{j,\ell}\left[\mathbf{b}_{j,\ell}; \boldsymbol{\rho}_{j,\ell}, \mathbf{a}_{j,\ell}\right] \tag{1b}$$

B. Theory: IAMs and the Social Cost of Carbon

Eqs. (1) are the core of a stylized, impacts- and adaptation-centric IAM presented in Figure 2. Its major feedback is the influence of current global fossil energy use on the regional and sectoral distribution of future productivities via the climate system (2j-k), the biophysical impacts of climate change (2l) and consequent shocks to the economy (2m). What is novel about our representation of this process is the detailed, one-to-one enumeration of endpoint-sector linkages. When climate damages bite, each regional social planner invests in reactive adaptation up to the point where its marginal opportunity cost in eq. (2f) just outweighs the contemporaneous marginal savings from damage reduction in (2c) and (2m). But the advantage of this model is its intertemporal structure, which permits the balance between discounted marginal future savings from proactive measures and the current marginal opportunity cost of the corresponding expenditure in (2f) to determine the incentive for accumulation of stock adaptation capacity in (2i) prior to the onset of damages.

The "social cost of carbon" (SCC) and the implications of adaptation for its value both readily fall out of this framework. For location ℓ' in some reference period t', the condition for optimal extraction of carbon-energy is $\frac{\partial \mathcal{W}}{\partial Q^E_{\ell',t'}} / \frac{\partial \mathcal{W}}{\partial Q^C_{\ell',t'}} = 0$, which yields the equilibrium condition:

$$
\begin{aligned}
\underbrace{\sum_{j=1}^{\mathcal{N}} \left(\frac{\partial \Phi_{\ell'}}{\partial q^Y_{j,\ell',t'}} \cdot \frac{\partial \psi_{j,\ell'}}{\partial q^E_{j,\ell',t'}} \cdot \frac{\partial q^E_{j,\ell',t'}}{\partial Q^E_{\ell',t'}} \right)}_{\text{Current marginal benefit}} = {} & \underbrace{P^E_{t'}}_{\substack{\text{Current marginal}\\ \text{extraction cost}}} \\
& \underbrace{+ \sum_{t=t'}^{T} \beta^{(t-t')} \sum_{\ell=1}^{\mathcal{L}} \left(\frac{\partial \Xi}{\partial U_\ell} \cdot \frac{\partial U_\ell}{\partial Q^C_{\ell,t}} \cdot \frac{\partial \Theta}{\partial Q^E_{\ell',t'}} \cdot Q^E_{\ell,t} \right) \Bigg/ \left(\frac{\partial \Xi}{\partial U_{\ell'}} \cdot \frac{\partial U_{\ell'}}{\partial Q^C_{\ell',t'}} \right)}_{\text{Resource stock effect of contemporaneous energy use}} \\
& \underbrace{\begin{aligned} & - \sum_{t=t'+1}^{T} \beta^{(t-t')} \frac{\partial \mathcal{E}}{\partial Q^E_{\ell',t'}} \Bigg/ \left(\frac{\partial \Xi}{\partial U_{\ell'}} \cdot \frac{\partial U_{\ell'}}{\partial Q^C_{\ell',t'}} \right) \\ & \times \sum_{\ell=1}^{\mathcal{L}} \left\langle \frac{\partial \Xi}{\partial U_\ell} \cdot \frac{\partial U_\ell}{\partial Q^C_{\ell,t}} \cdot \sum_{j=1}^{\mathcal{N}} \left\{ \frac{\partial \Phi_\ell}{\partial q^Y_{j,\ell,t}} \cdot \psi_{j,\ell,t} \cdot \sum_{i=1}^{\mathcal{I}} \left[\frac{\partial \lambda_{j,\ell}}{\partial b^i_{j,\ell,t}} \cdot \sum_{m=1}^{\mathcal{M}} \left(\frac{\partial \zeta^i_{j,\ell}}{\partial M^m_{\ell,t}} \cdot \frac{\partial \Upsilon^m_\ell}{\partial G_t} \right) \right] \right\} \right\rangle \end{aligned}}_{\text{Present value of future marginal climate damages}} \qquad \text{(3a)}
\end{aligned}
$$

The right-hand side of this expression is the SCC. Our interest is in the last term, the marginal externality cost of carbon-energy consumption, which, because it emanates from a globally wellmixed pollutant, turns out to be independent of the location in which the energy is consumed.[3]

As NRC (2010) emphasized, what makes the SCC difficult to calculate is the terms in curly braces. Carbon cycle science is sufficiently advanced to enable us to simulate with a fair degree of confidence the effect of the marginal ton of carbon on the time-path of future atmospheric GHGs ($\partial \mathcal{E} / \partial Q^E$). Similarly, global climate models have substantially improved their ability to simulate the future trajectory of consequent changes in temperature and sea levels at regional scales, though precipitation and ice/snow cover are still problematic (Bader et al., 2008). The key uncertainties are the future trajectory of emissions and the corresponding sequence of marginal climate responses to the accumulating stock of atmospheric GHGs ($\partial \Upsilon_\ell^m / \partial G$), the detailed marginals of the biophysical impact endpoints and productivity shocks (Table 1), and the projected output at risk in terms of regions' and sectors' contributions to future gross world product ($\partial \Phi_\ell / \partial q_{j,\ell,t}^Y \cdot \psi_{j,\ell,t}$).

An additional complication is that marginal impacts depend on the levels of stock and flow adaptation. This suggests that any value for the SCC must be predicated on assumptions made about adaptation investments in the future. In our canonical IAM the optimal levels of investment in a sector j' are determined implicitly from the first-order conditions $\frac{\partial \mathcal{W}}{\partial \rho_{j,\ell',t'}^i} / \frac{\partial \mathcal{W}}{\partial Q_{\ell',t'}^C} = 0$ and $\frac{\partial \mathcal{W}}{\partial \rho_{j,\ell',t'}^i} / \frac{\partial \mathcal{W}}{\partial Q_{\ell',t'}^C} = 0$, which yield in equilibrium:

$$\frac{\partial \Phi_{\ell'}}{\partial q_{j',\ell',t'}^Y} \cdot \psi_{j',\ell',t'} \cdot \left(\frac{\partial \lambda_{j',\ell'}}{\partial \rho_{j',\ell',t'}^i} + \frac{\partial \lambda_{j',\ell'}}{\partial b_{j',\ell',t'}^i} \cdot \frac{\partial \zeta_{j',\ell'}^i}{\partial \rho_{j',\ell',t'}^i} \right) = 1 \tag{3b}$$

and

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[3] We subtract the last term in eq. (3a) since the marginal effect of impact endpoints on productivity, i.e., $\frac{\partial \lambda_{j,\ell}}{\partial b_{j,\ell,t}^i}$, is negative, resulting in a negative present value of future marginal climate damages.

$$\sum_{t=t'+1}^{T} \beta^{(t-t')} \frac{\partial U_{\ell'}}{\partial Q^{C}_{\ell',t}} / \frac{\partial U_{\ell'}}{\partial Q^{C}_{\ell',t'}} \left(1-\vartheta^{i}\right)^{(t-t')} \times \left[\frac{\partial \Phi_{\ell'}}{\partial q^{Y}_{j',\ell',t}} \cdot \psi_{j',\ell',t} \cdot \left(\frac{\partial \lambda_{j',\ell'}}{\partial a^{i}_{j',\ell',t}} + \frac{\partial \lambda_{j',\ell'}}{\partial b^{i}_{j',\ell',t}} \cdot \frac{\partial \zeta^{i}_{j',\ell'}}{\partial a^{i}_{j',\ell',t}}\right)\right] = 1 \tag{3c}$$

Eq. (3b) shows that in the target period, the marginal benefit of flow adaptation on the left-hand side is equal to the marginal opportunity cost of foregone consumption of a unit of the final good. The first and second terms in brackets are the marginal productivity savings due to adaptive and defensive components of expenditure, respectively. Eq. (3c) has a similar form, but with the left hand side indicating the discounted stream of marginal benefits from the period-t' increment to the stock of adaptation capital.

We note that the system of equations (3) is a fixed point problem, as the implicitly-defined levels of carbon-energy consumption and adaptation investment themselves affect the values of the constituent derivatives. The implication is that the decisions to mitigate and adapt to climate change are generally not separable and should be considered jointly. In order to establish the optimal level of a carbon tax today we would need to solve the entire IAM in Figure 2 and compute the tax using the marginal externality component in eq. (3a), at $t' = 0$. In general, the initial value of the tax will be lower because of adaptation, but the further into the future impacts begin to bite, and the smaller the influence of adaptation, the less consequential this effect is likely to be.

C. Empirical Frameworks: Origins of the Disconnect with IAMs

Table 2 indicates that there has been a flurry of recent activity in the econometric analysis of the impacts of climate change. The typical approach, shown below, is a cross section-time series regression of a geographically and temporally varying indicator in a particular sector, $V_{j'}$

(e.g., profits, land values, crop yields), on fixed effects (α) to control for idiosyncratic influences associated with location, a time-trend or a vector of time dummies ($\boldsymbol{\chi}$) to capture the influence of unmeasured time-varying factors, polynomials of temperature (T), and, in some studies, precipitation (P) or other climate variables ($\mathbf{C}$), in addition to a vector of statistical controls ($\mathbf{Z}$):

$$V_{j',\ell,t} = \alpha_\ell + \boldsymbol{\chi}[t] + \underbrace{\eta_1^T T_{\ell,t} + \eta_2^T T_{\ell,t}^2 + \eta_1^P P_{\ell,t} + \eta_2^P P_{\ell,t}^2 + \mathbf{C}_{\ell,t}\boldsymbol{\eta}^C}_{\text{Climate Response Surface}} + \mathbf{Z}\boldsymbol{\gamma} \tag{4}$$

The parameter vector $\boldsymbol{\eta}$ is interpreted as the spatially-averaged marginal effect of the historical values of the climate variable on the sector in question. Once eq. (4) has been estimated, studies typically use the fitted values of the coefficients as a reduced-form response surface through which climate-model predictions of future temperature and precipitation can be run to obtain counterfactual values of V.

The crucial issue is the extent to which (4) adequately represents the behavior of the structural system of endpoint responses (1a) and productivity shocks (1b). One shortcoming is that climate tends to be represented simply in terms of temperature and precipitation, with some focus on tropical cyclones (Strobl 2008, 2009; Strobl and Walsh, 2008; Murphy and Strobl, 2010; Hsiang, 2010), but comparatively little attention to humidity (Barreca, 2011) or extra-tropical storms. Another limitation that is evident from Table 2 is the sparsity of geographic and sectoral coverage, with the vast majority of estimates being for the US, and the overrepresentation of aggregate income or output, or the agriculture and health sectors. However, the most fundamental problem is the conceptual disconnect with our process model and Table 1, in terms of whether the indicator in a particular study can be considered in the model as an impact endpoint, a follow-on productivity shock, or the ultimate economic damage from changes in climate.

Estimates of how changes in T and P directly impact income or output for entire national or regional economies, or coarse sectoral groupings, are analogous to aggregate damage functions which subsume a wide range of biophysical endpoints and sectors' responses to them (Dell et al 2008, 2009; Hsiang 2010). Estimates of the impacts on farm land values (Mendelsohn, Nordhaus and Shaw, 1994; Schlenker et al, 2006; Massetti and Mendelsohn, 2011) or profits (Deschenes and Greenstone, 2011) can be thought of as cross-impact, sector-specific damage functions which encompass a narrower range of endpoints to which a particular industry—in this case agriculture—may be exposed. Still other estimates of the income, price and employment impacts of an individual endpoint—most commonly, wind destruction from hurricanes (Strobl 2008, 2009; Strobl and Walsh, 2008; Murphy and Strobl, 2010)—can be thought of as cross-sectoral, impact-specific damage functions.

Only in a few studies does V appear to come close to our conception of a productivity index (crop yields—Schlenker and Roberts, 2008; Lobell et al., 2011; secular shifts in electricity demand—Aroonruengsawat and Auffhammer, 2011) or biophysical endpoint (the health outcomes of birth weight and mortality—Deschenes et al, 2009, Deschenes and Greenstone, 2011; Deschenes and Moretti, 2009; Barreca, 2011). But even so, yields are determined by the unobserved endpoints of soil moisture, evapotranspiration, and, where T and P lead to extreme weather events, storms or snowmelt resulting in runoff pulses that cause flood damage. Similarly, birth weight and mortality depend on underlying heat stress, and most likely its interaction with other unobserved co-morbidities, while residential and commercial electricity use are affected by temperature's influence on the latent demand for cooling services.

The elusive nature of the endpoints that constitute the channels through which T and P influence productivity suggests that (4) plays the role of a composite response function that collapses together (1a) and (1b). Given this state of affairs, it is worth asking how our IAM in

Figure 2 might be modified to take advantage of the types of empirical estimates that are forthcoming. A simple solution would seem to be to forgo the indexation of impacts by endpoint in favor of specifying region × sector trajectories of aggregate adaptation investments ($\tilde{\rho}_{j,\ell}$ and $\tilde{\pi}_{j,\ell}$) stocks ($\tilde{a}_{j,\ell}$), their opportunity cost and accumulation:

$$Q^{C}_{\ell,t} = Q^{Y}_{\ell,t} - X^{K}_{\ell,t} - P^{E}_{t} Q^{E}_{\ell,t} - \sum\nolimits_{j=1}^{\mathcal{N}} \left(\tilde{\rho}_{j,\ell,t} + \tilde{\pi}_{j,\ell,t}\right) \tag{2f'}$$

$$\tilde{a}_{j,\ell,t+1} = \tilde{\pi}_{j,\ell,t} + (1 - \tilde{\vartheta})\tilde{a}_{j,\ell,t} \tag{2i'}$$

and merging (2l) and (2m) into reduced form damage functions that translate climate variables directly into productivity shocks:

$$\Lambda_{j,\ell,t} = \omega_{j,\ell}\left[M^{1}_{\ell,t}, \dots, M^{\mathcal{M}}_{\ell,t}; \tilde{\rho}_{j,\ell,t}; \tilde{a}_{j,\ell,t}\right] \tag{5}$$

Two vital issues arise out of this new framework. The first is the question of what is lost by not considering detailed impact endpoints, and what biases might thereby introduced into projections of impacts economic and adaptational consequences. We feel it is important to ask this question, but currently have no means of providing an answer. One thing seems certain, however: our aforementioned adjustments leave little room to incorporate the findings of natural science process models on the climate's effects on impact endpoints. The bigger implication is that, in regard to strengthening the empirical basis of impact- and adaptation-centric IAMs, the current crop of econometric studies appears to be more of a substitute for than a complement to scientific investigations of impacts.

A final issue facing the empirical studies in Table 2 is the problem of controlling statistically for past adaptation. Precisely what component of firms' reallocation of inputs to production or individuals' behavioral or expenditure changes constitutes adaptation is unobservable, and must be inferred from secular trends or ancillary variables in $\mathbf{Z}$. The term $\boldsymbol{\chi}[t]$ in eq. (4) plays an especially important role in this regard. For example, Hsiang (2010), Schlenker and Roberts (2008) and Lobell et al (2011) model adaptation as region-specific timeaveraged responses, by grouping subsets of cross-sectional units into geographic neighborhoods (say $\mu(\ell)$), and specifying $\boldsymbol{\chi} = \sum_{\mu(\ell)} \chi_\mu (\delta_\mu \cdot t)$, where the regional dummy $\delta_\mu = 1$ if unit $\ell \in \mu$ and zero otherwise, t is a time-trend, and the χ_μs are parameters to be estimated. This specification allows cross-sectional units' long-run secular responses to differ, which has the potential to statistically capture (among other things) differences in rates of adaptation.

Nevertheless, the degree to which such statistical schemes do in fact compensate for a fundamental scarcity of data on adaptation remains to be seen. The concern is that estimates of eq. (4) suffer from omitted variable bias that leads to unmeasured adaptation responses imparting a downward bias the climate response function. If this occurs, incorporating the latter into eq. (5) can lead to double counting, in the sense that the mitigating effects of adaptation get commingled into the component of the function $\omega_{j,\ell}$ that is denominated over climate variables, causing it to understate the true magnitude of productivity impacts and induce sub-optimal adaptation expenditures. By contrast, what is desirable is a clean delineation of the pure effects of climate variables on one hand, and of adaptation on the other, the optimal trajectory of which is left entirely to the IAM to compute.

IV. Modeling Impacts and Adaptation: Recent Approaches

We are now in a position to survey the modeling literature on impacts and adaptation, using the conceptual, theoretical, and empirical frameworks of the previous section to critically examine analytical approaches that have been pursued over the past decade. To this end, it is useful to restate the key desirable features of an IAM:

- Impacts should be differentiated by, first, the geographic regions which are subject to various kinds of climatic shifts, second, the biophysical endpoint conduits through which changes in meteorology affect economy, and third, the economic sectors exposed to changes in productivity as a result.

- Adaptation should be differentiated along two dimensions. First, distinctions should be made between (I) passive market responses, (II) specific protective investments designed to shield sectors from impacts, and (III) specific adaptive investments designed to mitigate sectors' economic losses from impact-related shocks once the latter occur. Second, an IAM should distinguish proactive from reactive investments.
- The linkages between climate variables, impact endpoints and the productivity of economic sectors should be specified in a manner that substantially reflects empirical findings on impacts and adaptation.
- Optimal adaptation, be it of the Type I, II or III variety, should be undertaken in response to the intertemporal feedback of expected future economic damages from climate change, and should span uncertain states of the world. Adaptation should also be considered jointly with GHG emissions mitigation.
- Adaptation-related activities should be subject to induced technological progress as demand for them increases with the risk of climate damage. To capture this in IAMs, it may be necessary to distinguish between private and public investments and innovation.

Below we evaluate how well these are addressed by the modeling studies catalogued in Table 3. While there is much to be said on the first two points, the latter three are poorly handled in the vast majority of IAMs we review.

A. Global Intertemporal Models

Our discussion begins with global intertemporal models, since these are the closest to our canonical IAM in Figure 2. The strength of these models is their explicit incorporation of the intertemporal feedback effect of future climate damages on current energy use and abatement decisions, which they achieve by representing Figure 1's entire cycle of influences from emissions to climate impacts to damages over a multi-century horizon. However, largely for reasons of computational tractability, what ends up being sacrificed in the specification of damages is sectoral and impact endpoint detail, with all of the studies in this section using aggregate regional (or global) production functions denominated over labor, capital and energy, and damage functions denominated over global mean temperature. The aggregate scope of the economies thus represented subsumes general equilibrium effects and Type I adaptation.

When viewed though the lens of our conceptual framework, these models collapse both the endpoint and sectoral indexes, specifying instead aggregate regional adaptation investments ($\hat{\rho}_\ell$ and $\hat{\pi}_\ell$), stocks ($\hat{a}_\ell$), their opportunity cost and accumulation:

$$Q^C_{\ell,t} = Q^Y_{\ell,t} - X^K_{\ell,t} - P^E_t Q^E_{\ell,t} - \hat{\rho}_{\ell,t} + \hat{\pi}_{\ell,t} \tag{2f''}$$

$$\hat{a}_{\ell,t+1} = \hat{\pi}_{\ell,t} + (1 - \tilde{\vartheta})\hat{a}_{\ell,t} \tag{2i''}$$

while further aggregating the damage function (5) across sectors, and specifying global mean temperature ($\bar{T}$) as the sole climate variable of interest:

$$\widehat{\Lambda}_{\ell,t} = \Omega_\ell\left[\kappa_\ell[\bar{T}_t]; \hat{\rho}_{\ell,t}; \hat{\pi}_{\ell,t}\right] \tag{5'}$$

These changes to the structure of damages force consolidation of two other model components, on the input side meteorological variables generated by the reduced form climate model (aggregating over the index m):

$$\bar{T}_t = \Upsilon[G_t] \tag{2k'}$$

and on the output side the production function (collapsing eqs. (2b)-(2e)):

$$Q^Y_{\ell,t} = \widehat{\Lambda}_{\ell,t} \cdot \Phi_\ell\left[Q^K_{\ell,t}, Q^E_{\ell,t}\right] \tag{6}$$

The upshot is a simplification of the marginal externality cost of carbon-energy in eq. (3a) to:

$$- \sum_{t=t'+1}^{T} \beta^{(t-t')} \frac{\partial \mathcal{E}}{\partial Q^{E}_{\ell',t'}} \Big/ \left(\frac{\partial \Xi}{\partial U_{\ell'}} \cdot \frac{\partial U_{\ell'}}{\partial Q^{C}_{\ell',t'}} \right) \times \sum_{\ell=1}^{\mathcal{L}} \left\langle \frac{\partial \Xi}{\partial U_{\ell}} \cdot \frac{\partial U_{\ell}}{\partial Q^{C}_{\ell,t}} \cdot \Phi_{\ell,t} \cdot \frac{\partial \Omega_{\ell}}{\partial \bar{\bar{T}}_{t}} \cdot \frac{\partial \Upsilon}{\partial G_{t}} \right\rangle \tag{7}$$

This aggregate scheme essentially describes Nordhaus' RICE model (Nordhaus and Yang, 1996; Nordhaus and Boyer, 2000; Nordhaus, 2009), with the addition of Type II and Type III adaptation investments. Central to this approach is Nordhaus and Boyer's (2000) consideration of the temperature dependence of seven specific impact endpoints[4] and their aggregation together into regional damage functions, κ_{ℓ}. And, symptomatic of the empirical disconnect discussed above, these early estimates remain the foundation on which newer adaptation studies are based. De Bruin et al. (2009) introduce reactive adaptation, while Eboli et al (2010) add both reactive and proactive varieties of investments. To calibrate adaptation's mitigating effects these papers use the trick of splitting Nordhaus and Boyer's damage functions into the costs of adaptation and "residual" damages, utilizing estimates of damages from other models such as FUND and empirical results summarized in Agrawala and Fankhauser (2008) and UNFCCC (2007). Not surprisingly, the necessary empirical estimates are missing for many sectors and endpoints (e.g., other vulnerable markets; non-market use of time; catastrophic risks; human settlements) necessitating the use of assumptions to fill the relevant gaps. However, since the resulting adaptation and residual damage estimates are ultimately aggregated together at the regional level, is impossible to discern the extent to which guesses and interpolation influence their results.

B. Computable General Equilibrium Models

We next turn to computable general equilibrium (CGE) models, whose key feature is a multisectoral input-output representation of the economy—and, in the case of global CGE

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[4] Agriculture, sea-level rise, other market sectors, health, non-market amenity impacts, human settlements and ecosystems, extreme events and catastrophes.

models, the disaggregation of the world economy into regions linked by trade flows. For this reason, CGE models have the capability to represent in a comprehensive fashion the regional and sectoral scope of climate impacts—if not their detail—which of all the types of models considered can most easily accommodate region- and sector-specific climate damage functions.

But this advantage comes at the cost of inability to capture intertemporal feedbacks. Despite recent progress in specifying and solving forward-looking CGE models with optimal intertemporal capital accumulation (Lau et al, 2002), such analytical tools remain rare in the policy analysis domain. Where such models do exist computational constraints often limit their resolution to a handful of regions and sectors and a short time-horizon.[5] Thus, a common feature of the CGE models in Table 3 is that they are either static simulations of a future time period (e.g., Roson, 2003; Bosello et al 2006; 2007a,b) or recursive dynamic simulations that step through time driven by endogenous accumulation of capital with investment determined by current economic variables (e.g., Deke, 2001; Eboli et al, 2010; Ciscar et al 2011), and 2050 being the typical simulation horizon. Consequently, they lack the structure to simulate region- and sector-specific proactive investments, and restrict themselves to analyzing the welfare implications of Type I adaptations.

Except for Eboli et al (2010) and Ciscar et al (2011), CGE studies tend to investigate the broad multi-market effects of one or two impact endpoints at a time. The magnitudes of these forcing variables and their influences on the sectors in the model are determined exogenously and imposed as shocks to productivity or to the supply of climate-related fixed factors such as agricultural land. In the typical procedure, global climate models are forced with various scenarios of GHG emissions to calculate changes in climate variables at the regional scale,

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[5] e.g., the ADAGE model (Ross, 2007), which divides the U.S. economy into 9 regions, runs only to 2050. IGEM (Jorgenson and Wilcoxen, 1993; Jorgenson et al, 2004) runs out to 2100 but models the U.S. as a single region with sectoral detail.

giving rise to the reduced-from response surface, $\overline{\partial \Upsilon^m_\ell / \partial G_t}$. The outputs of this step are then run through natural science or engineering-based impact models to generate a vector of endpoint intensities in a particular impact category, say $\imath'$, resulting in the response surface, $\overline{\partial \zeta^{\imath'}_{j,\ell} / \partial M^m_{\ell,t}}$. The output of the latter is a region × sector array of shocks which form the inputs to counterfactual simulations of the CGE model, whose job it is to calculate the ex-post web of intersectoral and interregional adjustments, as a way of estimating the consequences for sectoral output, and regions' aggregate net products.

The result of these studies is the marginal effect on regions' welfare of variations in the magnitude and interregional or intersectoral distribution of particular types of impacts, which can be written formally as

$$\frac{\partial U_\ell}{\partial Q^C_{\ell,t}} \cdot \sum_{j=1}^{\mathcal{N}} \left\{ \frac{\partial \Phi_\ell}{\partial q^Y_{j,\ell,t}} \cdot \psi_{j,\ell,t} \cdot \frac{\partial \lambda_{j,\ell}}{\partial b^{\imath'}_{j,\ell,t}} \cdot \sum_{m=1}^{\mathcal{M}} \left(\overline{\frac{\partial \zeta^{\imath'}_{j,\ell}}{\partial M^m_{\ell,t}}} \cdot \overline{\frac{\partial \Upsilon^m_\ell}{\partial G_t}} \right) \right\} \tag{8}$$

The disconnect with the empirical literature is related to the first term in the parenthesis, which has so far tended to be derived from the results of engineering or natural science process models, not econometric studies. Notwithstanding this, eq. (8) suggests the possibility of undertaking comparative analysis of the welfare consequences of different impact categories, the purpose of which would be to establish their relative risks, conditional on our limited knowledge of the likelihood of their intensity. The results of such an exercise could potentially inform the allocation of effort in investigating how different impacts are likely to respond to climatic forcings at the regional scale.

Lastly, there appear to be ample opportunities to apply CGE models to evaluate the potential of specific adaptation investments. Climate mitigation-focused CGE models routinely embody speculative "backstop" energy technologies whose future characteristics are not precisely known, but which switch on and begin to moderate the future costs of GHG abatement once they become sufficiently high. Following the lead of de Bruin et al (2009), it is possible to undertake a similar analysis for adaptation, focusing on the reactive components of Type II and Type III investments. Likewise, Bosello and Zhang (2006) and Bosello et al (2010b) couple CGE and optimal growth models to introduce intertemporal feedbacks into the former as a way of inducing proactive adaptation investments. As before, the challenge is to improve the sectoral specificity of this procedure to the point where the proactive components of Type II and Type III investments can be simulated.

C. Sectoral Partial Equilibrium Models

Sectoral economic modeling studies constitute a third class of investigations. The strength of sectoral models is their detailed representation of the activities that constitute production within a particular area of the economy. The key limitation of their restricted sectoral coverage is an inability to capture multi-market general equilibrium effects. Since agriculture and forestry are the sectors most represented within this class of models, the implication is that this omission is more likely to bias estimates of the climate's economic consequences in poorer developing countries in which these activities make up a substantial fraction of GDP. The regional coverage of these models varies, with some (e.g., Rosegrant et al, 2008) being global in scope and resolving regional detail, but others (e.g., Adams et al, 1996) limited to a single region—most often the US. Also, along the time dimension, some models (Sohngen et al, 2001) are able to incorporate intertemporal feedbacks, while others are recursive dynamic (Rosegrant et al, 2008).

Sectoral studies rely on exogenous computation of impact endpoints, and follow the same procedure outlined above for CGE modeling, with the consequence that their connection with empirical impacts research is tenuous as well. Nevertheless, because of their detailed structural elaboration of the sector they consider, these models have the capability to more precisely resolve the channels through which different endpoints exert their effects over a limited economic domain. But currently it does not appear that this advantage has been exploited. Consequently, sectoral modeling results take the form

$$\psi_{j',\ell,t} \cdot \frac{\partial \lambda_{j',\ell}}{\partial b^{i'}_{j',\ell,t}} \cdot \sum_{m=1}^{\mathcal{M}} \left(\frac{\overline{\partial \zeta^{\iota'}_{j',\ell}}}{\partial M^{m}_{\ell,t}} \cdot \frac{\overline{\partial \Upsilon^{m}_{\ell}}}{\partial G_t} \right) \tag{9}$$

which, as explained before in the context of eq. (8), fails to consider specific adaptation investments, either reactive or (in the case of intertemporal models) proactive. Addressing this limitation is a priority for future research.

D. Other Simulation Models

Our final category of studies includes those that employ models which do not optimize an economic objective, but instead simulate the interconnected feedback relationships that underlie the diagram in Figure 1. The two most widely cited models of this kind are PAGE (Plambeck et al, 2007; Hope, 2006) and FUND (Tol et al, 1995; Tol, 1995; Anthoff and Tol, 2008). Both models divide the world into a number of regions, each of which has multiple damage functions that correspond to “impact sectors”—a hybrid of our impact endpoint and economic sector categories. PAGE models only aggregate market and non-market damages, while FUND includes ten sectors.[6] Monetary damages are specified directly as functions of per capita income, which in both models is exogenous and scenario-driven, and global (FUND) or regional (PAGE) temperature changes. The latter are calculated from accumulated GHG emissions generated by applying time-varying emission factors to GDP, and result in marginal external costs of the form

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[6] Agriculture, forestry, water resources, energy consumption, sea level rise, ecosystems, human health (morbidity and mortality from diarrheal disease, vector-borne diseases, heat stress), and tropical cyclones.

$$\sum_{t=t'+1}^{T} \beta^{(t-t')} \sum_{\ell=1}^{\mathcal{L}} \left\langle \overline{\frac{\partial U_{\ell}}{\partial Q_{\ell,t}^{C}}} \cdot \sum_{j=1}^{\mathcal{N}} \left\{ \bar{\psi}_{j,\ell,t} \cdot \sum_{i=1}^{\mathcal{I}} \left[\frac{\partial \lambda_{j,\ell}}{\partial b_{j,\ell,t}^{i}} \cdot \sum_{m=1}^{\mathcal{M}} \left(\overline{\frac{\partial \zeta_{j,\ell}^{\iota}}{\partial M_{\ell,t}^{m}}} \cdot \overline{\frac{\partial \Upsilon_{\ell}^{m}}{\partial G_{t}}} \right) \right] \right\} \right\rangle \qquad (10)$$

The functional forms and parameterizations of these damage relationships draw on a wide variety of sources, from summaries of empirical work to model results, but the precise linkages are far from transparent, especially with respect to regional variations in underlying biophysical endpoints.

Adaptation is represented both explicitly and implicitly in these models. FUND simulates specific adaptation costs as a component of damages in the agricultural and coastal sectors, while treating adaptation implicitly in other sectors such as energy and human health through the reduction in regions' vulnerability to impacts with increasing wealth. In PAGE adaptation is applied parametrically by the analyst as a policy variable. It incurs costs but allows developed countries to reduce up to 90%, and developing countries to reduce up to 50%, of the economic impacts of climate change, and permits all regions able to mitigate up to 25% of non-economic impacts. An interesting feature of PAGE is its explicit treatment of uncertainty by incorporating stochastic catastrophic damages and explicitly specifying 31 key inputs to marginal impact calculations as probability distributions.

E. Unmet Challenges

Comparing this brief survey of existing work with the list of desirable features of impacts and adaptation models, several gaps stand out. First, none of these models includes decision making under uncertainty, and for good reason. It is difficult to do. Optimal growth models like DICE with intertemporal decision making are deterministic and fully forward-looking. Past approaches to modify such a model to be stochastic usually involve creating multiple States of the World (SOWs), each with different parameter assumptions and different probabilities of occurrence; indexing all variables and equations in the model by SOW; and adding constraints to the decision variables so that for all time periods before information is revealed, decisions must be equal across SOWs. The problem with this approach is that it rapidly becomes a very large constrained nonlinear programming problem, and often the model will not converge to a solution for more than a trivial number of SOWs. The general problem of decision making under uncertainty is a stochastic dynamic programming problem that requires the exploration of a large number of samples of outcomes in every time period. The challenge is to fully explore the sample space while keeping the model computationally tractable.

Second, adaptation-related technological change is largely absent in current models. Most models are calibrated using existing knowledge of adaptation strategies and costs with no allowance for improvements in these strategies and technologies. The AD-WITCH intertemporal model (Bosello et al, 2010a,b) does attempt to account for this by including investment in adaptation knowledge as a decision variable that competes with other types of investment. Investments in adaptation knowledge accumulate as a stock which reduces the negative impact of climate change on gross output. However, the lack of empirical studies on adaptation-related technological change limits the modelers' ability to calibrate their model based on empirical knowledge. In the case of AD-WITCH, adaptation knowledge investments only relate to R&D expenditures in the health care sector where empirical data exist. This suggests that more empirical research in this area is desperately needed.

Third, differences in adaptive capacity or differences in the ability of regions to adapt to climate change are also important to capture in model analyses given the implications for distributional effects but are typically not represented in existing models. The FUND model implicitly captures adaptive capacity in the energy and health sectors by assuming wealthier nations are less vulnerable to climate impacts. However, it seems that only one model, AD-WITCH, attempts to explicitly capture adaptive capacity through the inclusion of investments in adaptation knowledge as a decision variable. Not only does this variable capture R&D investments in adaptation-related technologies as discussed in the previous paragraph, it also captures expenditures to improve the region's ability to adapt to climate change. Issues arise, however, when the model is calibrated since the modelers were only able to identify one source of qualitative information on adaptive capacity (i.e., the UNFCCC (2007) report discussed above) which only covers four aggregate regions (Africa, Asia, small island developing States, and Latin America). Assumptions were then made to translate this information to the regional representation and model parameters in AD-WITCH.

Lastly, another area where empirical work to inform models is lacking is in the dynamics of recovery from climate change impacts. Most models represent climate damages as a reduction in economic output which is assumed to recover over time. Empirical work on thresholds and time to recover including factors that influence these variables could help inform models on the type of dynamics that should be captured in impact and adaptation analyses. Also, better techniques to translate results from empirical studies to models are needed since the sectoral and regional detail of empirical studies does not typically align with the sectoral and regional detail in models. In general, to address the disconnect between empirical studies and modeling needs, we as a research community need to devise better ways to facilitate communication between empirical researchers and modelers.

V. Concluding Remarks

This paper offers a critical review of modeling practice in the field of integrated assessment of climate change and ways forward. Past efforts in integrated assessment have concentrated on developing baseline trajectories of emissions and mitigation scenario analyses. A key missing component in IAMs is the representation of climate impacts and adaptation responses.

Through the examination of conceptual, theoretical and empirical frameworks for the analysis of climate impacts and adaptation, we identify five characteristics of an ideal IAM: regional and sectoral detail for impacts and adaptation strategies; distinct representation of the three types of adaptation—adaptation through market adjustments, protective/defensive expenditures, and adaptive/coping expenditures; intertemporal decision making under uncertainty; induced innovation in adaptation-related technologies; and connection with empirical work on impacts and adaptation.

Our review of existing IAMs finds that most models are severely lacking in most of these modeling features. Although CGE models are the best equipped to capture the regional and sectoral detail required, many models do not support this level of resolution. Most models also do not distinguish between the three types of adaptation, yet they are very different in terms of their impact on the economy. CGE models are designed to capture market adjustments and therefore can easily capture adaptation through market adjustments. This type of model is also capable of capturing adapative/coping expenditures as long as the regional and sectoral representation supports it. However, CGE models are typically not well-equipped to capture protective/defensive adaptation expenditures unless they are combined with an optimal growth model which supports intertemporal decision making. Although the existing optimal growth IAMs support intertemporal decision making, these models assume perfect foresight; no current model supports true decision making under uncertainty. Adaptation decisions are inherently intertemporal and are made under uncertainty; therefore, this is an important area where advancements in modeling techniques are desperately needed.

Although progress has been made on modeling technological change related to mitigation technologies, the few models that do include specific adaptation technologies do not adequately represent technological advancements in these technologies, especially advancements induced by increased demand for proactive/defensive adaptation options. Much of this is due to the severe lack of empirical work by which to parameterize a model with adaptation-related technological change. The lack of empirical studies to parameterize models or the disconnect between existing empirical studies and models, in our opinion, is a key factor in the model community's inability to improve the representation of impacts and adaptation in models. In our review of the empirical literature, we find that indicators estimated in empirical studies do not typically align with impact endpoints, productivity parameters or economic damage variables found in process-based IAMs. As a result, the few brave modelers who attempt to include impacts and adaptation in their models undergo heroic efforts to translate these indicators to something useful that can be incorporated into the model. As a result, these models are prone to criticism, scrutiny, and error. Therefore, to improve upon the representation of impacts and adaptation in models, a process by which to bridge the gap between empirical studies and models should be a major research priority of the community.

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Figure 1. Economic Damages from Climate Impacts: A Bottom-Up Framework

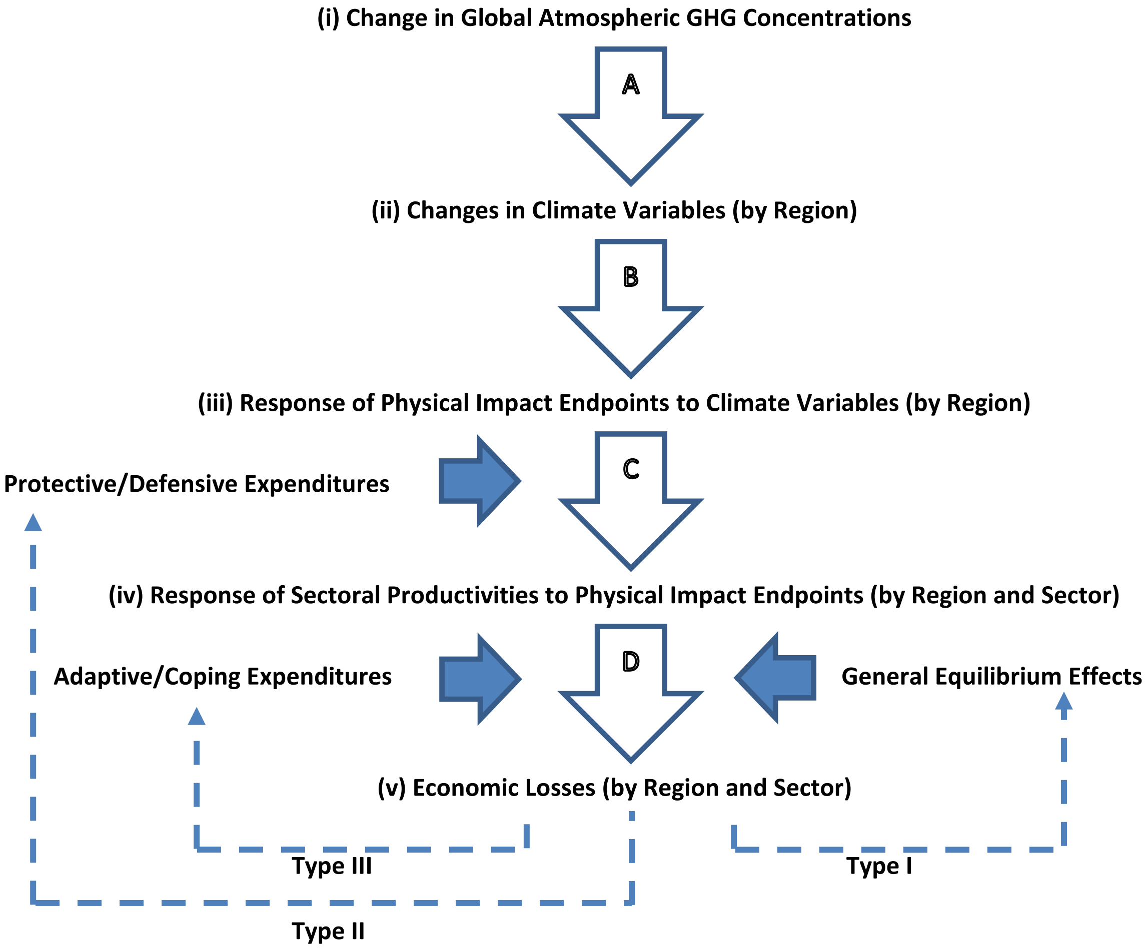

Figure 2. A Canonical IAM Incorporating Climate Impacts and Adaptation

A. Nomenclature

Set indexes:

$t = \{0, \dots, \mathcal{T}\}$	Time periods
$\ell = \{1, \dots, \mathcal{L}\}$	World regions
$j = \{1, \dots, \mathcal{N}\}$	Industry sectors
$m = \{1, \dots, \mathcal{M}\}$	Meteorological characteristics
$i = \{1, \dots, \mathcal{I}\}$	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
$X^{K}_{\ell,t}$	Aggregate jelly capital investment
$\rho^{i}_{j,\ell,t}$	Region-, sector- and impact-specific reactive adaptation expenditure
$\pi^{i}_{j,\ell,t}$	Region-, sector- and impact-specific proactive adaptation investment

Economic state variables:

$\mathcal{W}$	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
$a^{i}_{j,\ell,t}$	Stock of region-, sector- and impact-specific proactive adaptation capital

Environmental state variables:

G_t	Global stock of atmospheric GHGs
$M^{m}_{\ell,t}$	Region-specific climate variables
$b^{i}_{j,\ell,t}$	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
$\zeta^{i}_{j,\ell}$	Regional and sectoral climate impacts functions
$\lambda_{j,\ell}$	Regional and sectoral damage functions

Figure 2. A Canonical IAM Incorporating Climate Impacts and Adaptation (Continued)

B. Model Equations

Economic Sub-Model

Objective:

$$\max_{Q^C_{\ell,t}, q^E_{j,\ell,t}, q^K_{j,\ell,t}} \mathcal{W} = \sum_{t=0}^{T} \beta^t \Xi\left[U_1\left[Q^C_{1,t}\right], \dots, U_{\mathcal{L}}\left[Q^C_{\mathcal{L},t}\right]\right] \tag{2a}$$

Aggregate net regional product:

$$Q^Y_{\ell,t} = \Phi_\ell\left[q^Y_{1,\ell,t}, \dots, q^Y_{\mathcal{N},\ell,t}\right] \tag{2b}$$

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

$$q^Y_{j,\ell,t} = \Lambda_{j,\ell,t} \cdot \psi_{j,\ell}\left[q^E_{j,\ell,t}, q^K_{j,\ell,t}\right] \tag{2c}$$

Intra-regional and intra-temporal market clearance for energy:

$$\sum_{j=1}^{\mathcal{N}} q^E_{j,\ell,t} = Q^E_{\ell,t} \tag{2d}$$

Intra-regional and intra-temporal market clearance for jelly capital:

$$\sum_{j=1}^{\mathcal{N}} q^K_{j,\ell,t} = Q^K_{\ell,t} \tag{2e}$$

Aggregate regional absorption constraint:

$$Q^C_{\ell,t} = Q^Y_{\ell,t} - X^K_{\ell,t} - P^E_t Q^E_{\ell,t} - \sum_{i=1}^{\mathcal{I}} \sum_{j=1}^{\mathcal{N}} \left(\rho^i_{j,\ell,t} + \pi^i_{j,\ell,t}\right) \tag{2f}$$

Global energy trade and marginal resource extraction cost:

$$P^E_t = \Theta\left[\sum_{\ell=1}^{\mathcal{L}} \sum_{s=0}^{t} Q^E_{\ell,s}\right] \tag{2g}$$

Regional jelly capital accumulation:

$$Q^K_{\ell,t+1} = X^K_{\ell,t} + (1 - \vartheta^K) Q^K_{\ell,t} \tag{2h}$$

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

$$a^i_{j,\ell,t+1} = \pi^i_{j,\ell,t} + (1 - \vartheta^i) a^i_{j,\ell,t} \tag{2i}$$

Climate Sub-Model

Global atmospheric GHG accumulation:

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

Regional meteorological effects of global atmospheric GHG concentration:

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

Impacts Sub-Model

Biophysical climate impacts by type, sector and region:

$$b^i_{j,\ell,t} = \zeta^i_{j,\ell}\left[M^1_{\ell,t}, \dots, M^{\mathcal{M}}_{\ell,t}; \rho^i_{j,\ell,t}; a^i_{j,\ell,t}\right] \tag{2l}$$

Climate-induced productivity shocks:

$$\Lambda_{j,\ell,t} = \lambda_{j,\ell}\left[b^1_{j,\ell,t}, \dots, b^{\mathcal{I}}_{j,\ell,t}; \rho^1_{j,\ell,t}, \dots, \rho^{\mathcal{I}}_{j,\ell,t}; a^1_{j,\ell,t}, \dots, a^{\mathcal{I}}_{j,\ell,t}\right] \tag{2m}$$

Table 1. Key Responses in Modeling Climate Impacts and Adaptation

A. Regional Responses of Impact Endpoints with respect to Climate Variables

Region	**Impact Endpoint**	**Climate Variable**	**Modeling Studies**	**Empirical Studies**
Region 1	Endpoint 1	Temperature		
		Precipitation		
		Sea Level		
	Endpoint 2	Temperature		
		Precipitation		
		Sea Level		
	...			
	Endpoint *i*	Temperature		
		Precipitation		
		Sea Level		
Region 2	Endpoint 1	Temperature		
		Precipitation		
		Sea Level		
	Endpoint 2	Temperature		
		Precipitation		
		Sea Level		
	...			
	Endpoint *i*	Temperature		
		Precipitation		
		Sea Level		
...				

B. Regional Responses of Sector Productivities with respect to Impact Endpoints

Region	**Sector**	**Impact Endpoint**	**Modeling Studies**	**Empirical Studies**
Region 1	Sector 1	Endpoint 1		
		...		
		Endpoint *i*		
	Sector 2	Endpoint 1		
		...		
		Endpoint *i*		
	...			
	Sector *j*	Endpoint 1		
		...		
		Endpoint *i*		
Region 2	Sector 1	Endpoint 1		
		...		
		Endpoint *i*		
	Sector 2	Endpoint 1		
		...		
		Endpoint *i*		
	...			
	Sector *j*	Endpoint 1		
		...		
		Endpoint *i*		
...				

Table 2. Recent Econometric Studies of Climate Impacts' Consequences

Study	Climate variable	Regional focus	Dependent variable
Multiple Endpoints, Multiple Sectors			
Dell et al (2008)	Temperature	136 countries	Growth rates of aggregate income, aggregate investment, agricultural output, industrial output, political stability
Dell et al (2009)	Temperature	Municipalities in 12 countries in the Americas	Labor income
Jones and Olken (2010)	Temperature, Precipitation	101 countries	Exports
Graff Zivin and Neidell (2010)	Temperature	U.S.counties	Labor supply and productivity
Multiple Endpoints, Single Sector			
Deschenes and Moretti (2009)	Temperature	U.S. counties	Mortality due to cold/heat waves
Turner et al (2010)	Temperature	Iceland	Population growth
Deschenes and Greenstone (2011)	Temperature, Precipitation	U.S. counties	Mortality
Hsiang et al (2011)	El Nino Southern Oscillation	170 countries	Hazard of civil strife
Barreca (2011)	Temperature, Precipitation, Humidity	U.S. counties	Mortality
Massetti and Mendelsohn (2011)	Temperature, Precipitation	U.S. counties	Agricultural land values
Lise and Tol (2002)	Temperature, Precipitation	210 countries	Tourism flows
Single Endpoint, Multiple Sectors			
Stobl (2008)	Cyclone winds	U.S. counties	Per-capita income growth
Murphy and Stobl (2010)	Cyclone winds	U.S. coastal cities	House prices, per-capita income
Stobl (2009)	Cyclone winds	31 Caribbean Basin countries	Per-capita income growth
Hsiang (2010)	Temperature, Cyclones	28 Caribbean Basin countries	Output of agriculture, tourism, 6 non-exposed sectors
Single Endpoint, Single Sector			
Schlenker and Roberts (2008)	Temperature, Precipitation	U.S. counties	Crop yields
Stobl and Walsh (2008)	Cyclone winds	U.S. counties	Construction employment
Deschenes et al (2009)	Temperature	U.S. counties	In-utero heat stress, birth weight
Aroonruengsawat and Auffhammer (2011)	Temperature	California zip codes	Electricity demand
Lobell et al (2011)	Temperature, Precipitation	170 countries	Crop yields

Table 3. Recent Integrated Assessment Modeling Studies of the Economic Consequences of Climate Impacts

Study	Regional Scope	Sectoral Focus	Remarks
Global Intertemporal Economic Modeling Studies			
de Bruin et al. (2009)	Global	Aggregate	Uses AD-DICE/AD-RICE model
Bosello et al (2010b)	Global (12 regions)	Aggregate with energy system detail	Uses AD-WITCH model
Nordhaus (2010)	Global (12 regions)	Aggregate	Uses RICE-2010 model
CGE Economic Modeling Studies			
Deke et al. (2001)	Global (11 regions)	Agriculture, Sea-level rise	Uses DART model (Klepper et al., 2003)
Darwin (1999)	Global (8 regions)	Agriculture	Uses FARM model (Darwin et al., 1995)
Darwin and Tol (2001)		Sea level rise	
Jorgenson et al (2004)	U.S.	Agriculture, Forestry, Energy, Water, Coastal protection, Air quality, Heat stress	Uses IGEM model (Jorgenson and Wilcoxen, 1993)
Bosello et al (2006)	Global (8 regions)	Health	Uses GTAP-EF model (Roson, 2003)
Bosello and Zhang (2006)		Agriculture	
Bosello et al (2007a)		Energy demand	
Bosello et al (2007b)		Sea level rise	
Berittella et al (2006), Bigano et al (2008)	Global (8 regions)	Tourism, Sea level rise	Couples HTM and GTAP-EF models
Eboli et al (2010)	Global (14 regions)	Agriculture, Energy demand, Health, Tourism, Sea level rise	Uses ICES model
Bosello et al (2010a)	Global (14 regions)		Couples AD-WITCH and ICES models to investigate adaptation
Ciscar et al (2011)	Europe (5 regions)	Agriculture, Sea-level rise, Flooding, Tourism	Uses GEM-E3 model (Capros et al, 1997)
Literature Surveys			
Agrawala and Fankhauser (2008)	Multiple regions	Coastal zone, Agriculture, Water resources, Energy demand, Infrastructure, Tourism, Health	Survey of studies providing sector-specific estimates of adaptation costs generated by sectoral economic simulations
World Bank (2010)	6 developing regions	Infrastructure, Coastal zones, Water supply and flood protection, Agriculture, Fisheries, Health, Extreme weather events	Sector-specific estimates of adaptation costs, generated by combining dose-response functions with engineering analyses and sectoral economic simulations
UNFCCC (2007)	Asia, Latin America, Africa, Small island states	Agriculture, Water resources, Health, Terrestrial ecosystems, Coastal zones	Summarizes vulnerability, current and future adaptation plans/strategies, drawing on UNFCCC national communications, regional workshops, expert meetings.

Table 3. Recent Integrated Assessment Modeling Studies of the Economic Consequences of Climate Impacts (Continued)

Study	Regional Scope	Sectoral Focus	Remarks
Sectoral Partial Equilibrium Economic Modeling Studies			
Block et al. (2008)	Ethiopia	Water, Agriculture	Uses IMPACT model (Rosegrant et al., 2008)
Nelson et al. (2010)	Global (281 regions)	Water, Agriculture	
Butt et al. (2005, 2006)	Mali	Agriculture	Uses MASM model
Atwood et al. (2000)	U.S. regional	Agriculture	Uses ASM model (McCarl et al., 1998)
McCarl et al. (2000)	U.S.	Forestry	Uses FASOM model (Adams et al., 1996)
Sohngen et al. (2001)	Global (9 regions)	Forestry	Uses an optimal control model (Adams et al., 1996)
Other Simulation Studies			
Tol (2008)	Global (16 regions)	Health	Uses FUND model (Tol, 1995; Anthoff and Tol, 2008) which has regional damage functions for impact end-points (species loss, agriculture, coastal protection, disease morbidity/mortality, cyclones, migration, ecosystems, sea-level rise).
Tol (2007), Nicholls et al. (2008)		Sea level rise	
Narita et al. (2010)		Cyclones	
Link et al. (2004)		Multisector	
Anthoff et al (2011)		Multisector	
Hope (2006)	Global (8 regions)	Aggregate	Uses PAGE model (Plambeck and Hope, 1996)
Bigano et al. (2005; 2007), Hamilton et al. (2005a,b; 2007)	Global (207 countries)	Migration	Uses HTM model