Focus Article

Modeling impacts and adaptation in global IAMs

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Integrated assessment models (IAMs) of climate change combine dynamic descriptions of the energy-economy system, the climate system, and climate impacts to support the formulation of global, and possibly regional, climate policy. Originally they have been designed to inform mitigation policy but some of them are now applied in the context of adaptation policy as well. This article reviews the modeling of climate impacts and adaptation in global IAMs, including both models with an economic focus and models with a science focus. Key advances in the representation of climate impacts in IAMs during the last decade include improved consideration of differences in impacts across regions, the development of nonmonetary reduced-form climate impact models, and coupling of global IAMs with regional and sectoral impact models to assess climate change together with other sustainability issues. Further advances include a stronger focus on probabilistic analysis and attempt at considering large-scale climate instabilities. Adaptation has received only limited attention in global IAMs so far, mostly due to the mismatch in spatial scales at which mitigation and adaptation decisions are generally made. Some recent IAMs attempt to identify optimal levels of adaptation in climate-sensitive sectors or do include adaptation to climate change explicitly as a decision variable. The main reason for the consideration of adaptation in global welfare-maximizing IAMs is to assess the sensitivity of mitigation targets to different assumptions about the magnitude and effectiveness of adaptation. IAMs with geographically explicit impact models may also provide information that is useful for adaptation planning. *WIREs Clim Change* 2010 1 288–303

Integrated assessment models (IAMs) of climate change combine dynamic descriptions of the energy-economy system, the climate system, and climate impacts to support the formulation of climate policy. There is a wide variety of IAMs, which reflect the diversity of decision contexts in global climate policy as well as the range of underlying scientific disciplines. IAMs differ in the extent to use monetary values, the spatial resolution, the consideration of uncertainty, and the underlying decision-making framework.

Applications of IAMs can be broadly distinguished into policy optimization, policy evaluation, and policy guidance. Because IAMs have generally been designed to be applied in one of these decision-analytical frameworks, it is common to speak of policy optimization models, policy evaluation models, and policy guidance models, respectively. There is, however, some overlap between these categories, as witnessed by the application of some policy evaluation models (e.g., PAGE) and policy guidance models (e.g., ICLIPS) in policy optimization mode. Policy optimization models are designed to determine the 'best' climate policy as defined by an aggregated welfare function over time, possibly considering user-specified climatic constraints. Their complexity is severely limited by the numerical algorithms used to solve optimization problems. Furthermore, wide-ranging subjective assumptions are necessary to aggregate all consequences of alternative policies in a social welfare function to be maximized. Policy evaluation models (also known as simulation models) evaluate the effects of specific policies on various social, economic, and environmental parameters. Because these models are not subject to the computational constraints of optimizing models, they can include a much higher level of process and regional detail and provide more

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detailed information on the consequences of alternative policies. Policy guidance models determine all policies that are compatible with a set of subjectively specified constraints ('guardrails'). Their ability to consider multiple independent criteria in evaluating the acceptability of a given policy strategy does not require the heroic assumptions necessary for formulating an aggregated welfare function in policy optimization models. Because the algorithms applied by policy guidance models are similar to those of optimization models, they also require a highly simplified representation of dynamic system components.

Another important distinction of IAMs is their degree of spatial detail. Optimizing models either apply global averages or distinguish a limited number of geopolitical regions. Most policy evaluation models, in contrast, determine climate impacts on a geographical grid (often 0.5° latitude by 0.5° longitude). Some IAMs use different spatial resolutions in different submodules.

IAM analyses can also be distinguished according to their consideration of uncertainty. Deterministic analyses apply best-guess values for all model parameters. The simplest and most common approach to consider uncertainty is sensitivity analysis where uncertain parameters are varied one at a time. A more thorough treatment of uncertainty is through stochastic simulation, where probability distributions are specified for several uncertain model parameters and inputs and the results are determined as a probability distribution. Some models have been developed to address uncertainties from the outset, whereas others have been modified later to allow for probabilistic analysis. Finally, adaptive analyses (also known as sequential decision making under uncertainty) denote probabilistic applications of optimizing models that allow for future learning about key scientific or policy uncertainties. Note that the term 'adaptive' in this context is not related to 'adaptation to climate change'.

This article reviews the modeling of climate impacts and adaptation in global IAMs, focusing on the development in these areas during the last decade. Section 'Review of recent IAMs' presents the recent literature on impacts and adaptation in IAMs and provides an overview of all recent IAMs. Based on this overview, Section 'Modeling of impacts in IAMs' reviews the development and state of the art of climate impacts modeling in IAMs, and Section 'Modeling of adaptation in IAMs' reviews the development and state of the art of adaptation modeling. Section 'Challenges and opportunities' discusses possible ways forward for climate impacts and adaptation modeling in IAMs. Section 'Conclusions' concludes this article.

REVIEW OF RECENT IAMs

Several reviews of IAMs have been published recently. For general reviews of IAMs, see Refs 1, 2. About a decade ago, Tol and Fankhauser[3] have reviewed the modeling of impacts in 18 IAMs that participated in the Stanford Energy Modeling Forum 14. Their review discusses the level of spatial detail, the damage categories considered, the impact metrics, the climatic and nonclimatic drivers of impacts, the functional specification and benchmarks of monetized damage functions, the feedback of impacts on other model variables, and the representation of adaptation. Yohe[4] briefly reviews the representation of impacts in 20 IAMs, including most of the models considered by Tol and Fankhauser.[3] Stanton et al.[5] review 30 climate-economy models, focusing on the treatment of four critical issues. They conclude that none of the existing models incorporates the best practices on all or most of the questions examined in their review.

Hitz and Smith[6] survey studies that address global impacts of climate change as a function of the increase in global mean temperature (GMT). Their review includes biophysical modeling studies in sea level rise, agriculture, water resources, human health, energy, terrestrial ecosystems productivity, forestry, biodiversity, and marine ecosystems productivity as well as the monetized damage functions of three IAMs. Lecocq and Shalizi[7] review the empirical and theoretical literature on economic growth to examine how the four components of the climate change bill, namely mitigation, proactive and reactive adaptation, and climate impacts affect economic growth, especially in developing countries. The review includes nine optimizing IAMs but the focus is on the feedback of economic damages on future economic growth rather than on impacts modeling.

de Bruin et al. and Patt et al.[8,9] review the consideration of adaptation in IAMs, focussing on models for intertemporal cost-benefit analysis at a global scale. The latter article also suggests ways for an improved treatment of adaptation by considering more of its bottom-up characteristics. Finally, Dickinson[10] presents a review of different types of adaptation models. This review includes some global IAMs, but most of the models are concerned with the evaluation of regional and/or sectoral adaptation options.

This article adds to this body of literature by reviewing recent developments in the modeling of impacts as well as adaptation in global IAMs. The review includes all recent IAMs that allow for the comparison of mitigation targets and specific impacts of climate change. The specific criteria for the inclusion of a model are as follows:

1. Global coverage:

   The model must be global or include various regions that together cover the whole world. Models focussing on regional impacts or adaptation (e.g., IGEM, CLIMPACTS, CanCLIM, RegIS2, and other models reviewed in Ref 10) are not included in the table.

2. Full vertical integration:

   The model must include an energy/economy module, a climate module, and a representation of climate impacts. Hence, climate-economy models without explicit representation of impacts (e.g., most general equilibrium and cost minimization models reviewed in Ref 5) and models that only assess the probability of triggering a specific tipping element (e.g., dimrise[11]) are not included. The same applies to the coupling of exogenous climate scenarios with sector-specific impact models (e.g., GIM,[12] DIVA,[13] and the UK 'fast-track' studies[14,15]).

3. Real-world data:

   The model must include quantitative data aimed at resembling the real world. Purely theoretical or conceptual models (e.g., ISIS,[16] NeDym,[17] and the unnamed partial equilibrium model presented in Ref 18) are not included.

4. Active development:

   The model must have been in active development since the review by Tol and Fankhauser.[3] Inactive models (e.g., CONNECTICUT, SLICE, CETA, CSERGE, MARIA, PEF, PGCAM, DIAM, AS/ExM, FARM, TARGETS, HCRA, PGCAM) are not included in order to avoid duplication with Ref 3. In addition, variants of existing models are only included if the representation of impacts and/or adaptation differs from the earlier model. For instance, PRICE,[19] ENTICE,[20] and ENTICE-BR[21] are not included because they apply the original DICE damage function but AD-DICE is included.

5. Peer-reviewed:

   The model must be described in the peer-reviewed literature. If an earlier model version is described in a peer-reviewed article, presentation of the most recent model version in a working paper or conference proceeding is considered sufficient.

Note that the requirement for full vertical integration excludes several models that are regarded as IAMs in other reviews.[5,9,10] Table 1 presents an overview of all IAMs that match the criteria above. The letter 'b' marks those models where an earlier version has already been reviewed in Refs 3, 4. A detailed review of these IAMs will be presented in the following sections.

IMPACTS MODELING IN IAMS

Various approaches have been pursued for representing climate change impacts in IAMs. The main representations of impact in IAMs include geographically explicit biophysical impact models (e.g., for climate-related yield changes, disease incidence, and flooding of coastal areas) on the one hand and globally aggregated or regional monetary damage functions on the other. Monetary damage functions have been derived from a combination of case studies for selected regions or countries (most often the United States), cross-sectional analysis (i.e., studies that extrapolate current variations in economic productivity or other relevant variables across climate zones into the future), formal expert assessment, and 'guesstimates' by the modeler.

The choice of impact metrics in an IAM is largely determined by the underlying decision-analytical framework. Dynamic welfare maximization models, the most common category of policy optimization models, require an intertemporal social welfare function that aggregates all climate impacts across time, regions, impact domains, and uncertain states of the world (in stochastic analysis). While climate impacts do not necessarily have to be monetized (the welfare function could aggregate monetary and nonmonetary welfare components), all recent IAMs based on this framework apply monetary damage functions. Cost minimization models, another category of policy optimization models, generally specify a greenhouse gas concentration target or a climate stabilization target rather than an impacts target. One exception concerns the ICLIPS model, a policy guidance model that has been applied in cost minimization mode with a biophysical impacts target. Most climate-economy models based on a general or partial equilibrium approach do not include an impacts module. Policy evaluation models can represent climate impacts in different ways. Most of them include complex, geographically explicit impacts models, whereas others apply monetary damage functions. Policy guidance models require aggregated but not necessarily monetized impacts for the specification of guardrails for maximum tolerable

TABLE 1 | Modeling of Climate Impacts and Adaptation in Recent Integrated Assessment Models (IAMs) (See Text for Details)

Model			Approach		Drivers of Impacts			Representation of Impacts				
Name	References	Notes	Type	Uncertainty	Change in Mean Climate	'Other' Climate Change	Non-climatic[a]	Resolution	Metrics	Sectors	Feedback	Adaptation
DICE-2007[b]	22	Uses impact information aggregated from RICE-2004	Opt	Det, Prob, Adapt	glTemp	—	—	Global	Mon	—	GDP	Imp
AD-DICE	23	Global damage function for optimal adaptation identical to DICE-99	Opt	Det	glTemp	—	—	Global	Mon	—	GDP	Con (continuous): reallocation of production factors and budgets
MERGE 5.1[b]	24, 25	Damage function derived from DICE-92	Opt	Det, Prob	glTemp	—	—	9 regions	Mon	Mar, nMar	GDP, utility	Imp
RICE-2004[b]	26, 27		Opt	Det	glTemp	—	—	13 regions	Mon	—	GDP	Imp
WITCH	28, 29	Regional damage functions identical to RICE-99	Opt	Det	glTemp	—	—	12 regions	Mon	—	GDP	Imp
AD-RICE	8	Regional damage functions for optimal adaptation identical to RICE-99	Opt	Det	glTemp	—	—	13 regions	Mon	—	GDP	Con (continuous): reallocation of production factors and budgets
AD-FAIR	30	Impacts and adaptation identical to AD-RICE	Opt	Det	glTemp	—	—	17 regions	Mon	—	GDP	Con (continuous): reallocation of production factors and budgets
GRAPE	31	Damage function is very similar to RICE	Opt	Det	glTemp	—	—	10 regions	Mon	—	GDP	Imp
FUND 3.3[b]	32, 33	Some impact modules (e.g., for health) include nonmonetary impact representations	Opt	Det, Prob	glTemp (level, rate), gSea, CO_2	Wind storms, river floods	Income per capita, urban population	16 regions	Mon, (Bio)	Wat, Ag, For, En, Co, He, Set	GDP (including investment), population	Ind: agriculture; Opt: coasts
WIAGEM	34, 35	Applies impact functions from FUND 2.0 in a disputed way Refs 36, 37	Opt	Det, Prob	glTemp (level, rate), gSea, CO_2	Wind storms, river floods	—	11 regions	Mon	Wat, Ag, For, Eco, Co	Investment, population	Ind
PAGE2002[b]	38–42	Adaptation increases tolerable level and rate of temperature rise	Eval, Opt	Prob	regTemp (level, rate)	Unspecific large-scale discontinuity	—	8 regions	Mon	Mar, nMar	—	Scen (binary)
MiniCAM[b]	43, 44	Impacts and adaptation only considered when MiniCAM is coupled with AgLU	Eval, Opt	Det	regTemp, regPrec	—	Technology	11 regions	Bio, Mon	Ag, For	GDP	Rule: land allocation

TABLE 1 | Continued

Model			Approach		Drivers of Impacts			Representation of Impacts				
Name	References	Notes	Type	Uncertainty	Change in Mean Climate	'Other' Climate Change	Non-climatic[a]	Resolution	Metrics	Sectors	Feedback	Adaptation
AIM (2003)[b]	45	AIM/Impact: FOOD, HEALTH, VEG, HYDRO, WATER	Eval	Det	locTemp, locPrec, locCloud	—	Urban/ rural population density, income per capita, technology, dietary preferences	Grid; 30 regions, selected countries	Bio, Mon	Wat, Ag, For, Eco, He	—	Pol: water use efficiency improvement, flood mitigation, land use (only in COUNTRY model)
IMAGE 2.4[b]	46	Soft links to Water GAP, LPJ, and GLOBIO 3	Eval	Det	locTemp, locPrec, locCloud, CO_2	—	Land use, population density, dietary preferences	Grid; 24 regions	Bio	Wat, Ag, For, Eco, En	Carbon cycle, albedo	Rule: land allocation; Pol: trade policies
ICLIPS	44, 47–49	Uses impact modules from IMAGE 2.1 (TVM) and WaterGAP 1.1, aggregated to CIRFs	Guard	Det, Prob	locTemp, locPrec, locCloud, CO_2	—	—	Grid; 11 or more regions	Bio	Wat, Ag, For, Eco	—	Rule: crop switching (some aggregated indicators); land allocation (when linked with AgLU)
CIAS	50	Initial version includes ecosystem CIRFs from ICLIPS and a hydrological module	Eval	Det, Prob	locTemp, locPrec, locCloud, CO_2	—	—	Grid; 11 or more regions	Bio	Wat, Eco	—	N.A.
IGSM2[b]	51,52	Global Land System (GLS)	Eval	Det	regTemp, regPrec, regCloud, CO_2, O_3	—	Land-use change	34 latitude bands	Bio	Wat, Ag, For, Eco, He	GDP, agricultural trade, land vegetation change, carbon cycle	Rule: land use, agricultural trade
ICAM-3[b]	53, 54	Taken from Ref 3, because insufficient information is available on ICAM-3	Eval	Prob	regTemp (level, rate), regPrec	—	Population density	11 regions	Mon, Bio	Co, He, other Mar, other nMar	GDP, utility	Ind

CIRF, climate impact response function; GDP, gross domestic product.
[a]Includes dynamic variables that are modeled endogenously other than GDP, consumption, and income for monetary impact metrics.
[b]Earlier version of this model reviewed in Ref 3.
Type: Policy **opt**imization, policy **eval**uation, **guard**rail analysis;
Uncertainty: deterministic, **prob**abilistic, **adapt**ive;
Climate variables: global or **reg**ional or **loc**al (i.e., gridded) **temp**erature, **prec**ipitation, **cloud**iness/insolation, **sea** level, **CO_2** concentration, **O_3** concentration;
Metrics: monetary damages, **bio**physical units;
Sectors: market, **nonmar**ket, **wat**er, **ag**riculture, **for**est, natural **eco**systems, **co**astal zones, **he**alth, **en**ergy, **sett**lements and infrastructure; and
Adaptation: implicit, **ind**uced (transition time and/or costs), **scen**ario variable (without costs), **opt**imizing (considering costs and benefits), **cont**rol variable (with costs), **n**ot **a**pplicable, **rule**-based (nonmonetary optimization), **pol**icy variable (nonmonetary choice).

climate impacts. The only available policy guidance model refrains from monetizing climate impacts.

Several other impact metrics have been applied or suggested in the literature. The UK fast-track assessment[55] describes climate impacts by the number of people severely affected ('millions at risk'), but this aggregated impact metric has not been taken up by any IAM. Schneider et al.[56] suggested five impact metrics: monetary loss, loss of life, quality of life, biodiversity loss, and distribution/equity. Monetary losses are most widely included in IAMs. Interestingly, even when IAMs do estimate loss of life from climate change (e.g., FUND), their developers have chosen to include these impacts in the monetary damage estimates rather than reporting mortality figures separately. There has been some attention to the distributional aspects of climate impacts across regions in analyses with FUND[57] and GIM,[12] whereby the latter is not a full IAM. Biodiversity loss is difficult to quantify but several nonoptimizing IAMs have considered ecosystem transformation, including IMAGE[58] and ICLIPS.[47,59]

The most recent comprehensive review of impacts modeling in IAMs is already more than a decade old.[3] The IAMs included in that review differ widely with respect to the damage categories considered, the measurement unit, and the level of spatial detail. All optimizing models represented climate impacts by globally aggregated or regionally specific monetary damage functions, which represent climate damages as a fraction of (global or regional) gross domestic product (GDP). The functional relationship between climate indicators and (market) impacts was typically devised by the authors and fit to a limited number of impact assessments. Despite the impressive number of optimizing IAMs considered, monetized impact estimates were found to be '*based on a rather narrow set of studies*' and '*Damage modules are often not more than ad hoc extrapolations around the 2*CO_2 benchmark*'.[3] Table 1 shows that this characterization largely applies to more recent IAMs as well.

The damage functions of DICE-2007, AD-DICE, MERGE 5.1, RICE-2004, WITCH, AD-RICE, and AD-FAIR are all derived from damage estimates of Nordhaus and coauthors. They represent climate damages as a second-order polynomial of the increase in GMT. The main progress compared to earlier versions of the DICE/RICE models and their derivatives is that the recent damage estimates are based on a broader range of studies, including more impact assessments outside the United States. Furthermore, several scholars have modified DICE to account for large-scale climate instabilities, in particular a breakdown of the thermohaline ocean circulation (THC).[60–66] The damage function of GRAPE has the same form as that of RICE but applies somewhat different (and only partly documented) parameters.[31] Although the title of the respective article suggests that GRAPE addresses adaptation, this is not actually the case.

The damage functions of FUND 3.3 and WIAGEM are based on damage estimates by Tol and coauthors. There are a number of important differences between the DICE/RICE and FUND damage functions. First, climate impacts in DICE/RICE are driven exclusively by the change in GMT, and a single damage function attempts to represent climate impacts on all sectors considered, assuming optimal adaptation. FUND, in contrast, estimates separate damage functions for the following sectors: water, agriculture and forestry (including CO_2 fertilization), energy consumption (space heating and cooling), coasts (wetland loss, dryland loss, and protection costs), human health (diarrhoea, vector-borne diseases, cardiovascular, and respiratory mortality), and settlements and infrastructure. These damage functions are based on the combination and extrapolation of globally comprehensive studies using geographically explicit climate change-based scenarios. Second, climate impacts in FUND are driven by the level and rate of GMT change, sea level change, wind storms, river floods (whereby the last three climate variables are assumed to change linearly with GMT), and CO_2 concentration. Third, most welfare-optimizing IAMs represent climate damages as losses to income, although many impacts entail losses in capital stocks and reductions in productivity. FUND is unusual in that it models damages as reductions to both consumption and investment. Fourth, FUND describes health impacts using biophysical as well as monetary metrics. Literature-based estimates on deaths and disease incidence caused by climate change are converted into monetary damages based on the per capita income in the affected region. The functional forms of the relationship between climate variables and damages in each sector covered by FUND are largely based on expert judgement by Tol. FUND has also been applied to consider large-scale climate instabilities, such as a THC breakdown[67] and a collapse of the West Antarctic ice sheet.[68] Furthermore, FUND has been applied to compare the effects of different weighting schemes for regional impacts on the total damages from climate change.[69]

PAGE2002 is the third widely used IAM that applies monetized damage functions. In contrast to DICE/RICE and FUND, PAGE2002 has originally been developed as a policy evaluation model. More recently, however, it has also been applied to

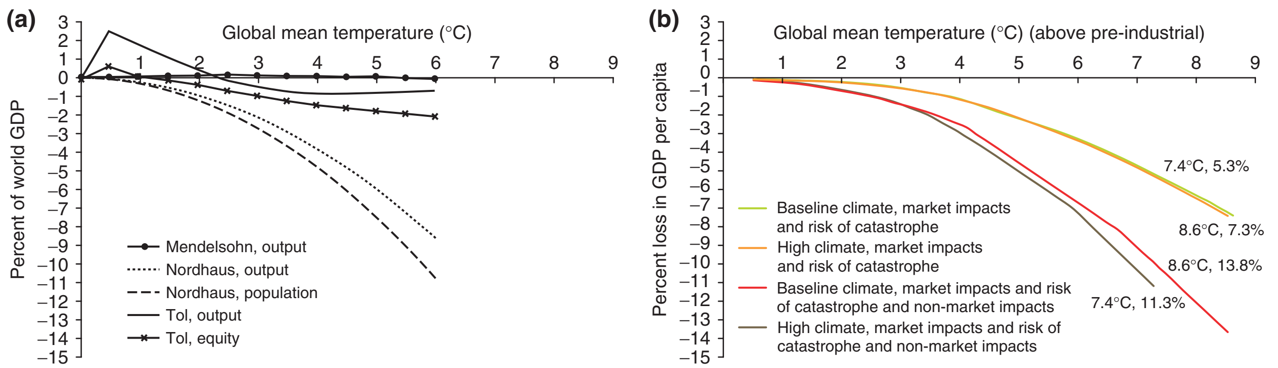

FIGURE 1 | Global damage functions, as a percentage of global gross domestic product (GDP), derived from different integrated assessment models (IAMs). Source: (Reprinted with permission from Ref 73. Copyright 2007 Cambridge University Press).

determine 'optimal' climate mitigation policies.[41,42] Climate damages in PAGE2002 depend on the level and rate of regional rather than global temperature change to account for the regional cooling effect of aerosols. The empirical basis comprises impact studies from the early 1990s, whereby an unspecified climate discontinuity has been included in PAGE2002. Because PAGE2002 has been specifically developed for probabilistic assessment of climate change, all parameters of the damage function are characterized by probability distributions rather than single best estimates.

MiniCAM is distinguished from other optimizing IAMs because it does not attempt to cover all major impacts of climate change. MiniCAM can be coupled to the AgLU model, which calculates biophysical and monetized impacts of climate change on crop yields and forestry. Other climate-sensitive sectors are not mentioned in the most recent description of MiniCAM,[43] although they apparently have been included in earlier model versions.[70]

Figure 1 compares monetized global damage functions from different IAMs. The left-hand diagram is derived from GIM,[12] RICE-99,[26] and FUND 2.0.[35] The right-hand diagram is from the Stern review,[71] which applied PAGE2002.[39] Note that a recent (unnamed) update of PAGE2002[40] models even higher damages from climate change. Figure 2 shows some of the key factors that influence estimates of the social costs of carbon (i.e., the marginal damage for an additional unit of carbon emitted), which is one of the

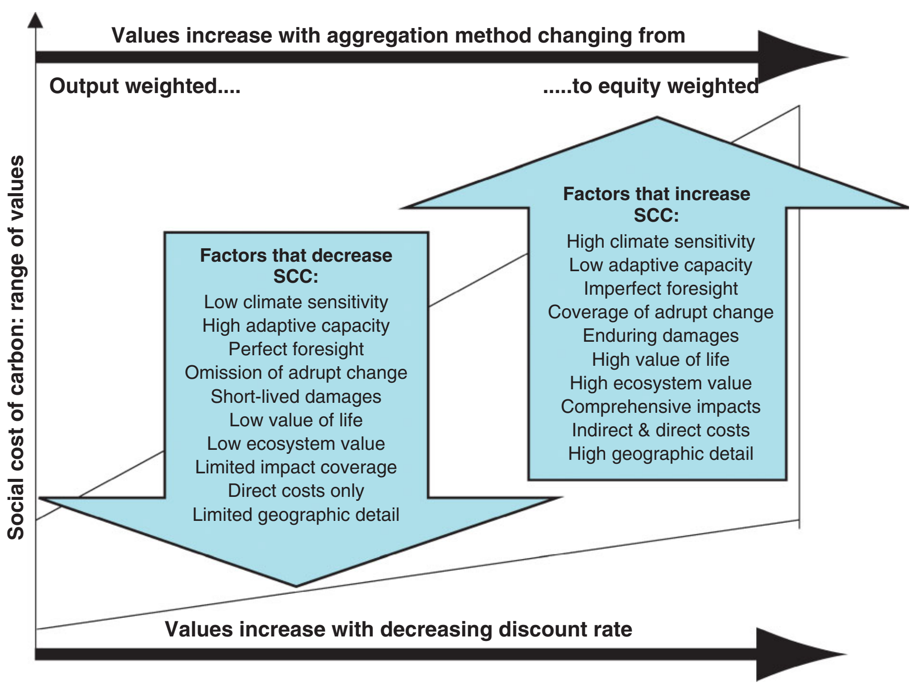

FIGURE 2 | Factors influencing the social costs of carbon. Source: (Reprinted with permission from Ref 74. Copyright 2007 Cambridge University Press).

main applications of IAMs with monetized damage functions.[72]

Some of the limitations of aggregated damage functions in IAMs include the often arbitrary or underexplained choice of exponents and other parameters and the common representation of damages in terms of losses to income, not capital.[5] Another limitation concerns a seemingly subtle but important incongruence at the interface between reduced-form climate models, which estimate the *expected* temperature change for a given emission scenario, and damage functions, which report damages for an *actual* level of temperature change. Because all damage functions applied in IAMs rise faster than linear (generally quadratic) with the level of climate change, the damages for the expected level of temperature change substantially underestimate the expected damages from climate change. Further limitations include the necessity for subjective choices in the aggregation of climate impacts across time and—in regionalized models—across space. The latter aggregation often applies Negishi welfare weights[75] that implicitly impose an assumption that human welfare is more valuable in richer parts of the world.[5]

Most policy evaluation models reviewed in Ref 3 (with the exception of PAGE) include complex climate impact modules driven by gridded climate projections. This is still the case for many recent policy evaluation IAMs (AIM, IMAGE, and CIAS). These models simulate geographically explicit impacts of climate change on a similar range of sectors—water, agriculture, forestry, natural ecosystems, and some of them also human health and energy demand—driven by gridded projections of changes in temperature, precipitation, cloudiness, and possibly CO_2 concentration.

AIM is distinguished from the other policy evaluation models by two features. First, biophysical impacts of climate change on agriculture are monetized and used as input to a trade model to assess higher-order social impacts, in particular on food security. The combination of crop yield estimates with trade models has been common in sector-specific climate impact and adaptation studies but not in IAMs. Second, the global AIM model is extended by various national models (AIM/COUNTRY) that allow assessing the combined impacts of global climate change and national policies at a much higher resolution than is possible with a uniform global model.

IGSM2 differs from other policy evaluation models by its coarser spatial resolution. Whereas the biosphere module of IGSM1 was applied at the 'usual' 0.5° by 0.5° resolution, the Global Land System (GLS) module of the more recent IGSM2 simulates biosphere and hydrology within 34 latitudinal bands *defined by the IGSM2 atmosphere dynamics and chemistry submodel*. IGSM2 considers human health but it focuses on the indirect impacts of climate change policies via air pollution rather than on the direct impact of climate change on human health.

The characterization of ICAM in Table 1 has been taken from Ref 3, because the only description of its climate impact module available in publications on ICAM-3 provides insufficient detail: *'the impact from climate change is calculated as a function of temperature change, its rate of increase, an estimate of the agricultural sector as a fraction of the economy, and coastal zone damages due to sea level rise'* Ref 53 (p. 476).

The ICLIPS model is the only IAM that implements the policy guidance approach. It applies existing biophysical models (notably from IMAGE 2.1 and WaterGAP 1.1) at the 'usual' 0.5° by 0.5° resolution and aggregates their results to climate impact response functions (CIRFs) defined at the global level or at the level of geopolitical or ecological regions. CIRFs represent nonmonetary aggregated damage functions that can be used to establish guardrails for climate policy. The ICLIPS model has also been applied to assess the relationship between emission pathways and the likelihood of large-scale climate instabilities, such as a THC breakdown.[11] CIAS differs from the other IAMs by its modular structure. Rather than being a monolithic model built by one group, CIAS was developed to provide a framework that enables the linking of different modules in a flexible manner. The initial CIAS version includes ecosystem CIRFs from the ICLIPS model as well as a global hydrological model. A related approach is followed by AIM, which includes 20 modules, including modules for regional climate impacts (AIM/COUNTRY).

The main developments in impacts modeling since the review by Tol and Fankhauser[3] are as follows:

1. Several IAMs have been applied to consider large-scale climate instabilities, either by *ad hoc* modifications to the damage function (DICE, FUND, and PAGE) or by coupling with a dynamic reduced-form model (DICE and ICLIPS). In contrast, none of the geographically explicit IAMs considers large-scale climate instabilities because detailed climate scenarios of these hypothetical events are not generally available.
2. An increasing number of IAMs has been applied for probabilistic assessments using Monte Carlo

analysis. These studies have determined monetized damage functions that consider climate change uncertainties, optimal decision policies considering uncertain damage functions, and the probability of triggering large-scale climate instabilities.[63–65,72,76–81] Monte Carlo analysis is not currently feasible for geographically explicit IAMs due to computational constraints.

3. The development of an IAM that implements the policy guidance approach has motivated the development of CIRFs, which are nonmonetary reduced-form impact models.
4. Various efforts have been made to develop modular IAM systems. The CIAS framework has been specifically designed to enable the coupling of modules developed by different groups. Several other IAMs have been coupled with global or regional impact models that are not part of the 'core' model (MiniCAM, AIM, and IMAGE).
5. Several recent IAMs consider climate change in combination with other environmental and sustainability issues, such as air pollution and land use (AIM, IMAGE, and IGSM).
6. Several modeling groups have developed visualization tools that present results of the geographically explicit climate impact simulations without the need for running the full IAM. Examples include the IMAGE User Support System,[82] the ICLIPS Impacts Tool,[83] and AIM/Impact (Country).[45]

ADAPTATION MODELING IN IAMS

Adaptation is generally understood as any action aimed at reducing adverse impacts or exploiting beneficial impacts of climate change. Adaptation can reduce many adverse social and economic impacts from climate change (compared to a hypothetical no-adaptation case), but it generally comes at a cost. The potential for human adaptation to prevent or reduce biophysical changes is much more limited. For instance, the continued existence of the Great Barrier Reef cannot be ensured once temperature and ocean acidity become unsuitable for the key organisms that it is composed of. Note that the distinction between human impacts and adaptation is not always clear. For instance, outmigration from regions at risk from coastal flooding may be considered as a human impact by some and as human adaptation by others.

Virtually, all IAMs reviewed by Tol and Fankhauser[3] focus on the trade-off between damages due to climate change and the costs of mitigation. Adaptation is either ignored or only treated implicitly as part of the damage estimate. According to de Bruin et al.,[8] the situation has not evolved much since then, with the exception of several IAMs codeveloped by the first author of that study: AD-DICE, AD-RICE, and AD-FAIR. The situation is not all that bleak, however, because IAMs with nonmonetary impact metrics were not considered in this review. Table 1 distinguishes the following categories for the consideration of adaptation in IAMs with monetary damage functions (1–4) and biophysical impact functions (5–7):

1. Implicit: DICE, RICE, MERGE, and WITCH

   The DICE model originally based its damage estimates on Ricardian analysis, using data from the United States to calculate damages as a function of the degree of warming, and then applied that function globally. The regional version of DICE, RICE, applies on a region-by-region basis either Ricardian analysis or a production function approach within a general equilibrium framework, which again assumes shifts in production to minimize losses. Hence, the damage functions of DICE, RICE, MERGE, and WITCH implicitly assume optimal adaptation and tend to ignore the costs of adapting.

2. Induced and optimizing: FUND and WIAGEM

   FUND has developed damage functions from a large number of regional studies, each of which minimizes losses through adaptation wherever considered feasible. The reduced-form damage function for agriculture in FUND represents adaptation explicitly through transition time and costs. This is possible because the damage functions in FUND consider level and rate of global climate change, whereas those in DICE/RICE consider only its level. The damage function for sea level rise in FUND treats coastal protection as a continuous decision variable, which is optimized based on a cost-benefit approach developed by Fankhauser.[84] The assumption of optimal adaptation to sea level rise has been relaxed in one analysis to assess the trade-off between adaptation and mitigation for this sector.[32] Adaptation in other sectors is not modeled explicitly in FUND.

3. Scenario variable: PAGE

   PAGE represents adaptation as a scenario variable by allowing a binary choice between no adaptation and aggressive adaptation. This representation is based on the simple assumption that aggressive adaptation increases the tolerable level and rate of climate change and decreases the residual impacts. The specification of adaptation is unchanged throughout all model versions up to and including PAGE2002. A recent review has suggested that the assumptions regarding the effectiveness of adaptation in PAGE have been overly optimistic.[23] In response to this critique, a more recent (unnamed) variant of PAGE2002 makes less optimistic assumptions.[40]

4. Control variable: AD-DICE, AD-RICE, and AD-FAIR

   AD-DICE, AD-RICE, and AD-FAIR treat adaptation explicitly, by considering it as a control variable. The AD-DICE model separates the global damage function of DICE-99, which assumes optimal adaptation, into an adaptation cost and a residual damage cost component. The calibration applies assumptions on the fraction of adaptation costs in total damages and the level of avoided damages from Ref 85 in the calibration point of the DICE damage function. A similar approach is applied for AD-RICE, which is based on the regional damage functions of RICE-99. Using these calibrations, adaptation and mitigation decisions become separable in AD-DICE and AD-RICE. AD-FAIR applies the same damage function as AD-RICE.

5. Not applicable: CIAS

   Because CIAS is designed to link modules (including impact modules) flexibly, the inclusion of adaptation is dependent on its representation in those impacts modules. The original version of the CIAS model includes CIRFs from ICLIPS that describe the climate-induced changes in natural ecosystems. Human adaptation is considered to be largely irrelevant for this impact domain, as it is impossible to ensure the continued existence of an ecosystem after the climate has become unsuitable to sustain it.

6. Rule-based: ICLIPS, MiniCAM, IMAGE, and IGSM

   IAMs with geographically explicit impact models for human-managed systems generally contain rules that describe how the management changes ('adapts') in response to changing climatic and/or socioeconomic conditions. Agricultural adaptations in ICLIPS are limited to changes in planting dates, cultivars, and crop switching (for some aggregated impact indicators only). MiniCAM/AgLU, IMAGE, and IGSM additionally allow for changes in land use, some of which have also implications for mitigation policy. It is not clear whether other adaptations, such as changes in fertilizer use and expansion of irrigation, have been considered by any of these models.

7. Policy variable: IMAGE and AIM

   IMAGE can be applied to assess the combined effect of climate change and changes in trade policies on food supply. The national extensions of AIM/Impact are able assess the interaction between climate impacts and several national policies, including water use efficiency improvement, flood mitigation, and land-use change. As both models consider climate change in the context of other drivers, including demographic and socioeconomic change, these 'adaptation' policies are not primarily assessed as to their ability to reduce the impacts of climate change but to achieve broader sustainability goals.

Two developments in adaptation modeling since the review by Tol and Fankhauser[3] are worth highlighting. First, an approach has been developed to consider adaptation in policy-optimizing IAMs based on DICE/RICE. However, wide-ranging assumptions are required to determine the five parameters of the residual damage and adaptation cost functions of AD-DICE, based on the single calibration point of the original DICE damage function. Second, most policy evaluation models now consider several policies that may be regarded as adaptation to climate change, in particular regarding land allocation, crop management, international trade, and producers' and consumers' behavior. The treatment of adaptation in policy-optimizing IAMs with monetary impact metrics emphasizes those adaptation activities that are additional and largely separable from current activities. In contrast, the treatment of adaptation in policy-evaluating IAMs with nonmonetary impact metrics emphasizes that climate change is one among many determinants of human actions, some of which contribute to successful adaptation to climate change.

CHALLENGES AND OPPORTUNITIES

There are various challenges for modeling climate impacts in IAMs. Projections of biophysical impacts are affected by large uncertainties about future climate change (including potential large-scale climate instabilities and changes in extreme climate events) and other environmental changes (e.g., land-use change). Projections of human impacts are additionally affected by uncertainties about socioeconomic and technological development, and the adaptive capacity of societies. These challenges are due to limitations of the underlying science, and improved representation of impacts in IAMs must therefore come primarily out of disciplinary studies in climate-sensitive sectors. The systematic assessment and communication of uncertainties associated with specific model simulations should be a key concern for all IAM applications, particularly those of policy evaluation models.

Even if biophysical and social impacts of climate change were known with certainty, monetary impact projections would still be strongly affected by subjective choices regarding the aggregation of costs and benefits across time, space, social groups, market and nonmarket impact categories, and uncertain states of the world. These choices often dominate the outcome of the aggregation.[72,86] The challenge of aggregation is inherent to policy-optimizing IAMs, which require the aggregation of all climate impacts despite the unprecedented spatial and temporal scope of the climate problem. For a more detailed critique of the application of aggregated monetary damage functions for climate change, see Refs 5, 87–91. At the least, their responsible use requires a 'traceable account' of the main value judgements involved in the aggregation and an analysis of their sensitivity to alternative judgements.[56]

Adaptation is much more difficult to address in global IAMs than mitigation, for the following reasons. First, adaptation is highly localized and it is very hard for IAMs to capture the diversity of climate impacts, adaptive capacity, and costs within diverse regions and countries. Second, adaptation involves a more diverse range of actors and actions, which complicates the representation of adaptation in highly aggregated models. Third, adaptation is more difficult to separate from current activities, and there is no common performance indicator. As a result, it is difficult to determine the costs and effectiveness of adaptation. Fourth, adaptation is often constrained by noneconomic factors, including cultural preferences and the nonoptimal use of information by agents, which complicates modeling of likely or optimal adaptation. Finally, mitigation benefits are global, and mitigation costs can be shared globally through emissions trading. In contrast, the benefits and costs of adaptation occur mainly at the local or regional level, which severely limits the usefulness of globally aggregated analysis.

For a more detailed discussion of the challenges and opportunities for modeling adaptation in IAMs, it is useful to distinguish different purposes for including adaptation in IAMs:

1. Analyzing the trade-off between mitigation costs, adaptation costs, and residual impacts ('modeling adaptation to guide global mitigation')
   This type of analysis intends to assess alternative global climate policies by considering the global costs and benefits of different levels of global mitigation and adaptation. The results are most relevant for guiding mitigation efforts, whose public good characteristics suggest that targets should be set centrally. Any policy- optimizing assessment of adaptation and mitigation assessment faces the challenges inherent in monetary damage functions discussed earlier. In addition, it must express all adaptation efforts in monetary terms, although many of them represent nonmarket costs, such as loss of cultural traditions, and forced changes in social structure and individual behavior. Given these difficulties, Patt et al.[9] argue that the most important question that policy-optimizing IAMs can help answer is how sensitive the choice of an optimal or appropriate mitigation target is to the range of potential future adaptations. They note that varying adaptation between nothing and its optimal level in AD-DICE moves the optimal mitigation target from a 22% to a 16% reduction from baseline emissions by 2100, which is marginal compared to the range of mitigation targets that policy makers are currently considering. The gap between these two mitigation levels implies that these policy makers either (implicitly) apply other damage and mitigation cost functions than DICE-99 or that they do not choose the mitigation target based on a maximization of the net benefits of climate policies. It would be worthwhile to test whether the conclusion that different adaptation strategies in AD-DICE have a relatively limited effect on the optimal level of mitigation is robust under alternative specifications of damage, adaptation, and mitigation cost functions.

2. Analyzing the trade-offs between mitigation and adaptation financing ('modeling mitigation and adaptation to guide international adaptation funding')
   The Kyoto Protocol establishes a link between mitigation policies and international adaptation financing by using a levy on the Clean Development Mechanism to provide resources to the Kyoto Protocol Adaptation Fund. IAMs can assess international adaptation funding by comparing the resources raised by alternative

financing mechanisms with the financial adaptation needs determined either exogenously or endogenously depending on the level of mitigation. An analysis with AD-FAIR has found that current mechanisms for adaptation financing are clearly inadequate to provide the level of resources for adaptation to climate change in developing countries determined by the AD-RICE adaptation cost functions.[30] Such analyses could be extended by considering the costs of residual impacts in addition to adaptation costs, noting that any such cost estimates are highly controversial.

3. Assessing adaptation costs across regions ('modeling adaptation to guide international adaptation spending')
IAMs may, in principle, inform the allocation of resources from a global adaptation fund across countries by providing information on their respective adaptation needs. In addition to the scientific uncertainties regarding regional climate impacts and corresponding adaptation needs, however, such an application also raises important normative issues. First, the adaptation costs of a country depend crucially on the level of residual impacts deemed acceptable. Determining adaptation costs on the basis of cost-benefit analysis (e.g., as done in FUND for coastal protection) could result in particularly unjust outcomes when residual impacts are not considered. For instance, a poor country that is relatively easy to protect against sea level rise could 'claim' the costs for full protection of its coastline, whereas a country that is more difficult to protect may be left without assistance if coastal protection is modeled not to be cost effective there. Second, international support for adaptation will depend not only on the level of adaptation costs of a country but also on its ability to shoulder (part of) these costs.

4. Assessing the effects of adaptation on residual impacts of climate change ('modeling adaptation to guide the level of regional adaptation')
IAMs can, in principle, be applied to assess the trade-off between adaptation and residual impacts at the regional level. For example, FUND has been applied to determine residual impacts of sea level rise for different levels of coastal protection. Patt et al.[9] argue, however, that policy-optimizing IAMs are unsuitable for guiding adaptation because of the mismatch in spatial scale between global models and local adaptation needs and the irrelevance of adaptation targets for the design of efficient and equitable adaptation policies. Sectoral and regional models are generally more appropriate tools to assist the design and prioritization of regional adaptation measures.

5. Identify good adaptation policies ('modeling adaptation to guide the design of adaptation')
Geographically explicit IAMs can help designing adaptation strategies by assessing the effectiveness of proposed adaptation measures in reducing adverse climate impacts and their interaction with other policy domains. For instance, land-use models can analyze the interaction between shifts in cropping areas ('adaptation'), potential increases in bioenergy production ('mitigation'), and expansions of protected areas ('biodiversity protection'), including potential synergies, areas of conflict, and trade-offs between different goals. IAMs with nonmonetary representation of impacts have been coupled to sectoral (e.g., IMAGE) or regional (e.g., AIM) impact models, but many impact domains and adaptation policies are not currently covered by any IAM. This coupling approach can combine the strengths of global IAMs to analyze the relationship between global mitigation efforts and regional impacts with those of more detailed models to assess the relationship between specific regional policies and residual impacts. Specific model applications, however, would likely focus either on mitigation or on adaptation.

6. Identify likely adaptations ('modeling adaptation to understand the level of adaptation')
Adaptation modeling in IAMs has been concerned either with determining optimal levels of adaptation or with assessing alternative adaptation strategies. Models can also be used to understand the likely level and effectiveness of adaptation under different scenarios and assumptions. Such models would focus on the process of adaptation, including decision processes, transition costs, noneconomic constraints, and lag times.[9] It is currently not clear, however, how detailed 'adaptation process models' could be integrated with global IAMs.

CONCLUSION

Climate impact modeling in early IAMs could largely be distinguished into two categories. Policy-optimizing models based on a cost-benefit paradigm applied aggregated monetary damage functions driven by smooth changes in GMT (dubbed 'the same, only warmer'), whereas policy guidance models applied geographically explicit biophysical climate impact models. This characterization is still largely correct but the picture has become more differentiated recently. One policy optimization model (FUND) includes biophysical representations of some climate impacts, and several of these models have been modified to consider the possibility of large-scale climate instabilities. Most recent policy evaluation models consider climate change in combination with other environmental and sustainability issues, and they are increasingly coupled with sectoral and regional impact models to extend the capabilities of the core model for specific applications. The only policy guidance model (ICLIPS) applies nonmonetary reduced-form impact models, which combine elements of the two earlier model categories.

The consideration of adaptation also differs substantially across model categories. Until recently, all policy-optimizing models implicitly assumed optimal adaptation in their damage function. Considering the various noneconomic constraints to adaptation, these models likely underestimate the full costs of climate change. This assumption has recently been relaxed in some IAMs. In particular, AD-DICE and AD-RICE attempt to separate the residual damage and adaptation cost functions implicitly contained in the aggregated damage functions of DICE and RICE, respectively. Doing so, these models can treat mitigation and adaptation as separate control variables. Initial results of AD-DICE suggest that the optimal mitigation target is rather insensitive to the explicit consideration of adaptation. FUND has been applied to investigate the trade-offs between mitigation and adaptation for the impacts of sea level rise on coastal zones. The consideration of adaptation in policy-optimizing models is, however, severely hampered for two reasons that are in addition to the empirical and normative challenges faced by earlier policy-optimizing IAMs. First, it is confronted with large uncertainties about the costs and benefits of adaptation, where few empirical data is available in most sectors.[92] Second, the separation of efficiency and equity aspects, that is possible for mitigation due to its public good characteristics, cannot be applied to adaptation, which yields mostly local benefits. Considering these challenges, the most promising way forward appears to be improving the theoretical understanding of adaptation by means of conceptual models (such as those considered in Refs 7,18) and improving the empirical aspects of adaptation by a systematic collection of costs and effectiveness of adaptation measures from bottom-up studies.

Policy evaluation models increasingly consider management strategies that may be considered as adaptation to climate change. Their effectiveness in reducing the impacts of climate change is often difficult to assess because these management strategies usually respond to a broad set of environmental and socioeconomic conditions rather than to climate change only. Further coupling of global IAMs with regional and sectoral models would enable assessing the effects of various management strategies under different climate scenarios. Analyses with policy guidance models may be surprisingly insensitive to the consideration of adaptation, because impact guardrails have generally been defined for sectors where human adaptation has little potential (e.g., transformation of natural ecosystems) or on the basis of large-scale climate instabilities (e.g., breakdown of the THC).

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