On the representation of impact in integrated assessment models of climate change

Richard S.J. Tol[a] and Samuel Fankhauser[b]

[a] *Institute for Environmental Studies, Vrije Universiteit, De Boelelaan 1115, 1081 HV Amsterdam, The Netherlands*
[b] *Centre for Social and Economic Research on the Global Environment, University College London and University of East Anglia, UK*

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The paper provides an overview of attempts to represent climate change impact in over twenty integrated assessment models (IAMs) of climate change. Focusing on policy optimization IAMs, the paper critically compares modeling solutions, discusses alternatives and outlines important areas for improvement. Perhaps the most crucial area of improvement concerns the dynamic representation of impact, where more credible functional forms need to be developed to express time-dependent damage as a function of changing socio-economic circumstances, vulnerability, degree of adaptation, and the speed as well as the absolute level of climate change.

Keywords: climate change, impact integrated assessment modeling

1. Introduction

One of the key ingredients to an integrated assessment model (IAM) of the enhanced greenhouse effect is the representation of the impact of climate change. It is also one of the weakest points in current IAMs. The underlying research is young, although developing rapidly, and the findings are still uncertain – both the actual results, as well as their interpretation. Watson et al. [47] and Pearce et al. [33] assess the state of the art. This paper provides a survey of how selected IAMs have dealt with the challenge of impact modeling. The survey reflects the state-of-the-art of 1996. Alternative solutions are critically compared, and issues are identified which are collectively neglected or treated in a very *ad hoc* manner. Suggestions for improvement are made.

Integrated assessment modeling approaches are very diverse. Weyant et al. [48] distinguish two broad classes of IAMs: policy optimization models (such as *DICE*), which seek optimal policy strategies, and policy evaluation models (such as *IMAGE*), which assess specific policies. Optimization models are normative in character and typically analyze climate change from an economist's point of view, i.e., they focus on the efficiency and (individual and collective) rationality of a policy. The level of modeling detail permitted in optimization models is constrained by the need to keep the optimization algorithm tractable, and these models are therefore relatively small in size. Policy evaluation models on the other hand tend towards the natural sciences and, avoiding optimization, can contain considerably more detail.[1] A special category of IAMs that encompasses both optimization models (such as *SLICE*) and evaluation models (such as *ICAM*) places uncertainty analysis at the core of the modeling endeavour. As is the case with optimization IAMs, uncertainty models need to be small in size in order to allow proper uncertainty analysis and the computation of a large number of scenarios within reasonable time. Within and between these different categories of models, the approaches taken to represent climate change impact vary widely. The aim of the comparison presented here is to confront modelers with alternatives, to allow users a choice, to identify areas of (potentially false) consensus and dissensus, and to prioritize research.

While some more natural-science oriented models are also included in the survey, the emphasis in the paper is on economic-science oriented IAMs. The models analyzed in this article are listed in table 1.[2]

The paper deals with the following issues. Section 2 discusses the way impact is represented in the surveyed models, i.e., the impact categories included, the level of spatial disaggregation, and the way impact is measured (e.g., by using physical units, indices, monetized damages, safety standards, or multi-attribute utility functions). Section 3 investigates the functional specifications used in the different model, i.e., the level of disaggregation, the choice between process-based and reduced form specifications, the degree of non-linearity, the climatic parameters driving impact, and the climate/damage benchmark. Section 4 discusses the interaction of impact with the rest of the model,

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[1] Attempts to reconcile the two approaches are ongoing. The only published example (to our knowledge) is the *OMEGA* model of Janssen (1996). However, its damage module (the subject of this paper) is identical to *DICE*.

[2] The models are listed in no particular order. Models are selected on the basis of their involvement in the Energy Modeling Forum Round 14: Integrated Assessment of Climate Change (EMF14). The integrated assessment activities of IIASA and MIT have not been included since no fully coupled model is apparently built there. The *Policy Evaluation Framework* of USEPA/Decision Focus Inc. is excluded for want of model documentation.

Table 1
List of models surveyed.

Model	Source
DICE	Nordhaus [31]
CONNECTICUT	Yohe et al. [49]
SLICE	Kolstad [18]
RICE	Nordhaus and Yang [32]
AIM	Morita et al. [28,29]
MERGE 2	Manne et al. [22], Manne and Richels [23], Richels (personal communication, 1996)
CETA	Peck and Teisberg [34], Teisberg (personal communication, 1996)
IMAGE 2	Alcamo [1], Leemans (personal communication, 1996)
CSERGE(M)	Maddison [21]
CSERGE(F)	Fankhauser [11]
FUND 1.4, 1.5	Tol et al. [46], Tol [44]
PAGE 91, 95	Hope et al. [17], Plambeck and Hope [37,38], Plambeck et al. [36]
MARIA	Mori [25], Mori and Takahashi [26,27]
ICAM 2.0, 2.5	Dowlatabadi and Morgan [6], Dowlatabadi (personal communication, 1996)
MiniCAM 2.0	Edmonds et al. [7,8]
PGCAM	Edmonds et al. [7,8]
DIAM	Grubb et al. [13], Ha Duong (personal communication, 1996)
AS/ExM	Hammitt et al. [14], Lempert et al. [19,20]
FARM	Darwin et al. [4,5], Darwin (personal communication, 1996)

Models are listed in no particular order. Models are selected on the basis of their involvement in the Stanford Energy Modeling Forum, Round 14.

i.e., the way non-climatic parameters (economy, population, environment, policy) drive impact, and the way impact influences other model variables. The modeling of adaptation to climate change is also discussed in section 4. Section 5 presents conclusions, and identifies future research needs.

2. The representation and measurement of impact

This section discusses the basic assumptions underlying the impact modules of the surveyed IAMs. Key assumptions include: (i) the comprehensiveness of impact analysis, (ii) the level of spatial detail, and (iii) the measurement of impact. The models and their assumptions are displayed in table 2. The text refers to the tables as Tn-m, where n is the table and m the column. T2-2 is table 2, second column.

The surveyed IAMs deal with a wide variety of impacts (T2-2), including the effects of climate change on agriculture, energy, coastal zones (sea level rise), forestry, water, terrestrial vegetation, malaria, schistosomiasis, heat and cold stress, air pollution, migration, tropical cyclones, amenity, river floods, extratropical storms, tourism, mining, transport, and services. However, the set of included categories varies widely between models, and none of the surveyed IAMs deals comprehensively with all impacts.

Perhaps surprisingly, there is no clear trade-off between comprehensiveness (T2-2) and modeling detail (T2-3). Some IAMs that explicitly distinguish (T2-2), and model (T3-2), different impact categories do that for a range of impacts. Others included only a limited number. Some models that rely on an aggregate measure of impact (T2-3; e.g., the *DICE* family of models, *MERGE*, *CETA*, the *CSERGE* models, *MARIA*) obtain comprehensiveness by simply including a broad, but only vaguely defined residual category, “other damages” (originating from Nordhaus [30]). Others explicitly include reduced forms for a range of impact categories.

It should be noted, however, that IAMs reflect at best the state of the art of the underlying literature. The models using aggregate impact measures often just mimic one particular published estimate (see below which), thus mimicking its shortcomings and differences with other studies. Variations in the set of impacts covered may also reflect a difference in opinion about the scientific reliability of some impact estimates, either between IA modelers themselves, or as passed on from the underlying literature. The suggestion is, however, that, at least for a number of models, it would be relatively easy to extend and update their impact modules to existing information to better reflect the state of the art.

There are two ways in which IAMs provide spatial detail on impact (T2-3). Some, mostly natural-science-based models examine impact in a geographically explicit way, by dividing the globe into a series of grid-cells (e.g., *AIM*, *IMAGE*, *PGCAM*, *FARM*). Other models distinguish between different geo-political regions, thus specifying impact at a larger-scale regional level. In addition, there are several global models without spatial distinctions. The geo-political and global approaches are typically used in policy optimization and uncertainty models. Regional differences in impact have been increasingly stressed in the recent literature, a trend that is likely to increase, as better regional data becomes available (see, e.g., Watson et al. [47]). In keeping with this trend, IA modelers have worked on the regional resolution of their models, and the latest versions now generally provide much better regional detail than their predecessors. However, in most models, especially those using monetized damage estimates (compare T2-3 with T2-4), regional estimates continue to be extrapolations of estimates made for the USA (again reflecting the underlying literature).

Impact can be measured in a variety of ways, viz. as physical units, indicators, monetized damages, safety standard violations, or attributes to multi-attribute utility functions (T2-4). Physical units and monetary damages are by far the most popular approaches among the modelers. Economic models in their majority use monetized damages. Physical units are primarily utilized in science-based models that also represent damage in a geographically explicit way using grid cells. It should be noted that the “mone-

Table 2
The impact of climate change in selected integrated assessment models.

Model	Damage categories considered	Spatial detail	Measurement of impact
DICE	farming, energy, coastal activities, other	global	monetized based on Nordhaus [30]
CONNECTICUT	farming, energy, coastal activities, other	global	monetized based on Nordhaus [30]
SLICE	farming, energy, coastal activities, other	global	monetized based on Nordhaus [30]
RICE	farming, energy, coastal activities, other	six regions (USA, Japan, former Soviet Union, China, European Union (12), rest of the world)	monetized based on Nordhaus [31]
AIM	water, agriculture, forestry, natural vegetation, malaria	grid-based: $1/2$–$1/12°$	physical units[a]
MERGE 2	farming, energy, coastal activities, other	five regions (USA, other OECD, former Soviet Union, China, rest of the world)	monetized adjusted from Nordhaus [30]
MERGE 3	farming, energy, coastal activities, other	nine regions (USA, Western Europe, Japan, other OECD, Eastern Europe and former Soviet Union, China, India, Mexico and OPEC, rest of the world	monetized adjusted from Nordhaus [30]
CETA	farming, energy, coastal activities, other	global	monetized adjusted from Nordhaus [30]
CETA (revised)	wetland loss, ecosystem loss, heat and cold stress, air pollution, migration, tropical cyclones, coastal defense, dryland loss, agriculture, forestry, energy, water	six regions (USA, European Union, other OECD, former Soviet Union, China, rest of the world)	monetized adjusted from Fankhauser [11]
IMAGE 2	terrestrial ecosystems[b], crop distribution and productivity[c], biodiversity, water-availability, energy supply and demand, distribution of disease vectors	grid-based (0.5), 13 regions (Canada, USA, Latin America, Africa, OECD Europe, Eastern Europe, former Soviet Union, Middle East, India and South Asia, Centrally Planned Asia, East Asia, Australia and New Zealand, Japan)	physical units
CSERGE(M)	coastal defences, dryland loss, wetland loss, species loss, agriculture, forestry, water, amenity, heat and cold stress, air pollution, migration, tropical cyclones	global	monetized based on Fankhauser [9]
CSERGE(F)	coastal defence, dryland loss, wetland loss, ecosystems loss, agriculture, forestry, energy, water, heat and cold stress, air pollution, migration, tropical cyclones	global	monetized based on Fankhauser [11]
FUND 1.4	coastal defence, dryland loss, wetland loss, species loss, agriculture, amenity, heat stress, cold stress, migration, tropical cyclones	nine regions (OECD America, OECD Europe, OECD Pacific, Eastern Europe and former Soviet Union, Middle East, Latin America, South and Southeast Asia, Centrally Planned Asia, Africa)	monetized based on Tol [42]

Table 2
(Continued.)

Model	Damage categories considered	Spatial detail	Measurement of impact
FUND 1.5	coastal defence, dryland loss, wetland loss, species loss, agriculture, heat stress, cold stress, malaria, migration, tropical cyclones, river floods, extratropical storms	nine regions (OECD America, OECD Europe, OECD Pacific, Eastern Europe and former Soviet Union, Middle East, Latin America, South and Southeast Asia, Centrally Planned Asia, Africa)	monetized based on Tol [44]
PAGE 91	tourism, agriculture, mining, manufacture, utilities, transport, services, sea level rise, cultural (i.e., non-market)	four regions (European Union (12), other OECD, Eastern Europe and former Soviet Union, rest of the world)	monetized based on CRU/ERL [3]
PAGE 95	economic, non-economic	seven regions (European Union (12), other OECD, Eastern Europe and former Soviet Union, Africa and Middle East, Centrally Planned Asia, South Asia, Latin America)	monetized based on CRU/ERL [3], Fankhauser [10], Tol [42]
MARIA	coastal defence, dryland loss, wetland loss, species loss, agriculture, forestry, water, amenity, life/morbidity, air pollution, migration, tropical cyclones	four regions (Japan, other OECD, China, rest of the world)	monetized based on Fankhauser [9]
ICAM 2.0	sea level rise, other market, ecosystems, other non-market	seven regions (OECD America, other OECD, Eastern Europe and former Soviet Union, Latin America, South and Southeast Asia and Middle East, Centrally Planned Asia, Africa)	monetized based on Dowlatabadi and Morgan [6]; WTP (including thresholds and saturation)
ICAM 2.5	sea level rise, other market, health, other non-market	seven regions (OECD America, other OECD, Eastern Europe and former Soviet Union, Latin America, South and Southeast Asia and Middle East, Centrally Planned Asia, Africa)	monetized based on Dowlatabadi and Morgan [6]; WTP (including thresholds and saturation)
MiniCAM 2.0	market, non-market	eleven regions	monetized based on Manne et al. [22] (except where modeling is complex – cf. table 3)
PGCAM	agriculture, forestry, water, vegetation	grid-based (5° × 5°) plus sixteen regions	physical units
DIAM	damage	global	monetized
AS/ExM	damage	global	monetized
FARM	land and water resources, agriculture, forestry, other	0.5° × 0.5° for resources, 8 regions (USA, Canada, European Union (12), Japan, Other East Asia, South East Asia, Australia and New Zealand, Rest of the world)	physical indicators; monetized based on Hertel [15]

[a] Economic evaluation under development.

[b] Twenty land cover classes.

[c] Twelve crop types.

tized" models generally do not model underlying physical impacts. "Physical" models, on the other hand, generally do not have an interface to aggregate impacts or translate them into a common metric (such as money). This hampers the comparison of the outcomes of the two modeling approaches.

Monetization is based on a rather narrow set of studies. The main source is Nordhaus [30], followed by Fankhauser [9,11], Tol [42,45], CRU/ERL [3] and Hertel [15]. Interestingly, the seminal study by Cline [2] has not been directly used in any of the IAMs. Neither have the works by Hohmeyer and Gärtner [16] and Titus [40] been used. This selective choice from an already small basis need not necessarily be of concern, however, since most modeling teams rely on extensive sensitivity and uncertainty analysis. In addition, the underlying literature draws to a large extent upon the same sources. Recent work shows a divergence which may not be adequately captured. On the one hand, the study by Mendelsohn and Neumann [24] draws a more optimistic picture of climate change than the older studies, concluding that the impact of a modest climate change on OECD countries may well be positive. On the other hand, the work by Fankhauser et al. [12], looking into the distributional aspects of climate, concludes that incorporating notions of equity may well increase the impact estimates, at least, on a global scale. These studies, however, are too recent to have had an impact on IA modeling.

3. The functional specification of impact

This section discusses the characteristics of impact modules within IAMs along the following five criteria:

(i) the level of detail in climate and physical impact modeling;

(ii) the choice between a "process-based" and a "reduced-form" approach;

(iii) the assumed degree of non-linearity in the damage function(s);

(iv) the climatic parameters used as inputs in the damage function(s); and

(v) the benchmark around which damage is calibrated.

The models and their assumptions are displayed in table 3.

3.1. Reduced-form models

IAMs with limited spatial detail (T2-3) also tend to have little disaggregation with respect to the modeling of the biogeochemical processes governing climate change impact (T3-2). These models usually take a "reduced-form" approach (T3-3), that is, they attempt to describe the major features of climate change in a computationally efficient fashion. In a number of cases, as few as one or two equations – with regionally differentiated parameter values in some cases – are used to describe the impact of climate change.

In the case of one-equation modules, aggregate (usually monetized) damage (T3-2, T2-4) is modeled as a function of one (sometimes several) climate variables, the prime choice being the global mean surface air temperature (T3-5). The most popular approach is a power function, with the powers ranging from 1 to 3 (T3-4). Exceptions are *FUND*, using second-order polynomials, and *MERGE*, using a hockey-stick function of the form

$$D(\Delta T) = 1 - \left[1 - \left(\frac{\Delta T}{T_m}\right)^{\alpha}\right]^{\beta},$$

where T_m is the benchmark level of ΔT ($D = 1$ for $\Delta T = T_m$, that is, all income is spent on climate change) and $0 \geqslant \beta \geqslant 1$. If $\beta = 1$, the hockey-stick returns to a power function.

In the case of two-equation modules, the distinction usually is between market damages (which affect output, e.g., agricultural damages), and non-market damages (which affect utility, e.g., health impacts) (T3-2). In "reduced-form" modules (T3-3) with more than two equations (T3-2), each impact category would typically have its own equation. The advantage of separating impacts in this way is that it allows to reflect the fact that different categories may react differently to socio-economic development and other environmental pressures (T4-2), or may feed back differently into the other parts of the IAM (T4-4); see section 4.

Most reduced-form models use globally averaged figures as their main climatic inputs (T3-5). Exceptions are *PAGE 95, MERGE* and *ICAM 2.5*, which use region-specific temperature, *inter alia* to enable the analysis of the effect of sulphate aerosols. Interestingly, though, *MERGE* uses *global* mean temperature to drive non-market impacts. The case for this choice is not entirely clear. The most important non-market impacts are ecosystem and species loss, and human health risks. Of these, only biodiversity can be considered a global good affecting human wellbeing independently of its geographic location. The use value of many landscapes and ecosystems, on the other hand, tends to be local. Similarly, the effect of climate change on health risks will predominantly depend on local factors.

The main driver of impact in most reduced-form IAMs is the level of (global mean) temperature.[3] Only a few models consider both the rate and the level of change (e.g., *CSERGE(F), FUND, PAGE* and *ICAM*). *CETA* has also been used to study the impact of both the level and the rate of change (Peck and Teisberg [35]), but it does not allow to model both effects simultaneously. By focusing on the level of temperature, combined with the usual choice for a power function, most models implicitly assume that the current climate is optimal[4] (cf. Mendelsohn and Neumann [24] for a different perspective). Any deviation from

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[3] Note that *FUND* also regards sea level, wind storms and river floods. However, these variables depend linearly on temperature, being place holders for more complex specifications in future versions.

[4] Attention is usually restricted to increases in temperature.

Table 3

Characteristics of climate change impact modules in selected integrated assessment models.

Model	Aggregation	Approach	Non-linearity	Climate input	Benchmark
DICE	one function	reduced form	quadratic	global mean temperature	3°C: 1.33% GDP
CONNECTICUT	one function	reduced form	quadratic	global mean temperature	3°C: 1.33% GDP
SLICE	one function	reduced form	quadratic	global mean temperature	described by a probability distribution
RICE	one function	reduced form	quadratic	global mean temperature	2.5°C: 1.1% in USA to 2.1% in ROW
AIM	one or more models per category	process-based	complex	daily and monthly, regional temperature, precipitation, soil moisture and cloudiness	complex
MERGE 2	two functions (market, non-market)	reduced form	hockey-stick	regional mean temperature for market impacts; global mean temperature for non-market impacts	2.5°C: 0.25% (market) + 2% (non-market) GDP (developed) 0.5% GDP (market) + 4% (non-market) (developing)
MERGE 3	two functions (market, non-market)	reduced form	hockey-stick	regional mean temperature for market impacts (including aerosols); global mean temperature for non-market impacts	2.5°C: 0.25% (market) + 2% (non-market) GDP (developed) 0.5% GDP (market) + 4% (non-market) (developing)
CETA	one function	reduced form	linear, quadratic or cubic	global mean temperature (level or rate)	3°C: 2% GDP
CETA (revised)	two functions (market, non-market)	reduced form	power function	global mean temperature (level over pre-industrial)	2.5°C: 1.35% GDP
IMAGE 2.1	several models	process-based for biophysics, heuristics for socio-economics	complex	monthly temperature, precipitation and cloudiness	complex
CSERGE(M)	one function	reduced form	quadratic	global mean temperature	2.5°C: 1.5% GDP
CSERGE(F)	two functions (market, non-market)	reduced form	power (1.3) function, multiplied with factor for rate of change	global mean temperature (level and rate)	2.5°C at 2050: 1.4% world GDP (ranging from 0.7 in former Soviet Union to 4.7 in China)
FUND 1.4	separate functions for each category	reduced form	second-order polynomial	global mean temperature, sea level and hurricane activity (level and rate)	2.5°C + 0.04°C/yr, sea level: 0.17 cm/°C, hurricane: 17%/°C; 1.9% world GDP (ranging from −0.3% in former Soviet Union to 8.7% in Africa)
FUND 1.5	separate functions for each category	reduced form	second-order polynomial	global mean temperature, sea level, hurricane activity, river floods, and winter storms (level and rate)	2.5°C + 0.04°C/yr, sea level: 0.17 cm/°C, hurricane: 0%/°C, river floods: 4%/°C, winter storms: 2.4%/°C; 2.5% world GDP (ranging from −0.4% in former Soviet Union to 16.3% in South and Southeast Asia)
PAGE 91	separate functions for each category	reduced form	linear above mixed threshold, zero below; note: all thresholds set to zero in base case but are policy variables	global mean temperature (level and rate)	235.6×10^9 ECU/(°C in excess of threshold)

Table 3
(Continued.)

Model	Aggregation	Approach	Non-linearity	Climate input	Benchmark
PAGE 95	separate functions for economic and non-economic damage	reduced form	linear to cubic (best guess: 1.3) above mixed threshold, zero below; note: all thresholds set to zero in base case but are policy variables	regional mean temperature (level and rate)	1.3% (economic) plus 1.0% of GDP for 2.5°C in European Union – other regions vary from -0.23 (Eastern Europe and former Soviet Union) to 3.30 (South Asia) times this
MARIA	one function	reduced form	quadratic	global mean temperature	3°C: 1.4% (Japan), 1.5% (other OECD), 2.0% (China) and 1.7% (rest of the world) of GDP
ICAM 2.0	separate models or functions for each impact category	reduced form	complex	global mean radiative forcing, rate and level	market: 0.5% GDP (developed) and 2.5% GDP (developing) for $2 \times CO_2$ by 2025; non-market: 2% GDP (developed) and 0.5% GDP (developing)
ICAM 2.5	separate models or functions for each impact category	reduced form	complex	regional temperature (rate and level) and precipitation	market: 0.5% GDP (developed) and 2.5% GDP (developing) for $2 \times CO_2$ by 2025; non-market: 2% GDP (developed) and 0.5% GDP (developing)
MiniCAM 2.0	separate models for each impact category	reduced form	complex	regional temperature and precipitation (mean and variability); sea level	complex
PGCAM	separate models for each impact category	process-based	complex	regional temperature and precipitation (mean and variability); sea level	complex
DIAM	one function	reduced form	linear	annual global mean atmospheric CO_2 concentration (lagged)	$2 \times CO_2$: 2% of GDP
AS/ExM	one function	reduced form	power + triangular	annual global mean temperature	various choices
FARM	separate models for each damage category	process-based	complex	monthly temperature and precipitation, grid-based	complex

the present temperature is bad, and would result in perpetual losses. Although power functions with temperature as the only explanatory variable provide a useful starting point, they are evidently not realistic. More work is needed to better understand the intertemporal properties of damage and to incorporate these results into future IAMs (see Tol [43]).

With the exception of *MiniCAM*, the level of the sea is not calculated separately in reduced-form IAMs. Implicitly,[5] these models thus assume the sea level to be linearly dependent on temperature. This has two implications. Firstly, models using regional temperature levels miscalculate sea level rise. Secondly, and more importantly, by ignoring the thermal inertia of oceans, an incorrect time profile of sea level rise is used. If such a model were used to evaluate the impact of, say, concentration stabilization, the implied sea level rise and associated costs would be underestimated in the long run. Similarly, if a model were to evaluate strong sustainability (i.e., a stationary state of natural capital) it would wrongly conclude that stabilizing temperatures would be sufficient.

Except for *ICAM* and *MiniCAM*, the surveyed models do not consider precipitation. Implicitly, precipitation change is assumed to be linear in temperature change and impact is assumed to depend on a linear combination of precipitation and temperature. Both assumptions are questionable, and may have to be revised as better information on regional precipitation patterns becomes available.

Impacts of the surveyed reduced-form models are all calibrated around the usual $2 \times CO_2$ benchmark: doubling of pre-industrial CO_2 concentration in the atmosphere (T3-6). $2 \times CO_2$ is generally associated with a temperature rise of either 2.5 or 3.0 °C above present,[6] assumed to occur by about 2050.[7] IAMs that use monetized damages generally follow the available literature (e.g., Pearce et al. [33]) very closely, and assume benchmark damages ranging from 1.3 to 2.5% of world income, with considerable variation between regions (if distinguished).

3.2. Process-based models

More science-oriented and geographically explicit IAMs (T2-3) tend to have one or more modules operating per damage category (T3-2). These modules are generally "process-based", that is, they attempt to capture in a realistic fashion the mechanisms underlying the phenomena (T3-3). Consequently, they use a more elaborate set of equations and climatic inputs, and typically also consider precipitation, soil moisture, cloud cover and so on (T3-5). In addition, the temporal (up to daily) and spatial resolution (up to $15''$) is considerably finer (T2-3).

Reviewing the complex mathematical properties of these models (T3-4) would go beyond the scope of this paper. As noted in the introduction, the emphasis in this survey is on more economic-oriented IAMs which tend to use reduced-form representations.

4. Feedback and interaction

While the impact of climate change is an important part of an IAM, it is only one of several elements. This section describes the interactions of impact with the other parts of an IAM. It discusses: (i) non-climatic variables affecting impact; (ii) the process of adaptation; and (iii) the way in which impact is fed back into the rest of the model. The models and their assumptions are displayed in table 4.

The impact that climate change will have on society and ecosystems is largely determined in the interplay between climate on the one hand and vulnerability to weather events on the other. Arguably, vulnerability may thus be as important a determinant of impact as is climate change itself. It is somewhat disappointing therefore to note how little attention the majority of IAMs pay to this issue.

The vulnerability of human systems to climatic events depends to a large extent on such factors as technical and financial capability, demographic, socio-economic and behaviourial constraints and the organization of society. The vulnerability of non-human systems is also increasingly affected by human actions. As these factors develop over time, vulnerability to climate change is likely to change as well, and considerably so, over the next century. Nevertheless, IAMs barely deal with the issue of changing vulnerability. In the simplest representations, damage is expressed as a constant fraction of Gross Domestic Product (T4-2). That is, absolute damage is assumed to grow linearly with GDP. Lumped into this assumption are the effects of population growth (affecting the number of people impacted), income growth (affecting vulnerability as well as people's valuation of impact), changes in taste (affecting valuation), socio-economic structure (affecting the relative importance of impact categories), as well as several others. Few models explicitly consider, e.g., the influence of population density or health standards on vulnerability, or the effect of non-climate-change related environmental pressure.

Although adaptation is often identified as a potentially powerful way to reduce the adverse impacts of climate change, a substantial number of IAMs do not explicitly consider adaptation (T4-3). Implicitly or explicitly, models relying on aggregate monetized damage estimates usually adopt the damage-cum-adaptation philosophy used in that literature. That is, damage includes both the costs of adaptation (e.g., coastal protection) and the cost of residual damages (e.g., loss of unprotected land), but adaptation costs are neither explicitly distinguished nor is the assumed level of adaptation necessarily optimal (cf. Fankhauser [10], Yohe et al. [49]) or as observed (cf. Mendelsohn and Neumann [24]). Some models include induced adaptation, that is, the process of readjustment to a new climate is represented through transition costs and transition time. In

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[5] *FUND* does this explicitly.

[6] Note that the *CETA* and *CSERGE* models assume above pre-industrial.

[7] In the calibration of the damage modules; this assumption remained from older climatological studies, upon which most of the impact literature has been built.

Table 4

Interaction of impact of climate change with rest of the integrated assessment model.

Model	Non-climatic drivers	Adaptation	Impact feedback
DICE	damage linear in GDP	not explicitly considered	GDP scaled down with damage
CONNECTICUT	damage linear in GDP	not explicitly considered	GDP scaled down with damage
SLICE	damage linear in GDP	not explicitly considered	GDP scaled down with damage
RICE	damage linear in GDP	not explicitly considered	GDP scaled down with damage
AIM	drought-risk and malaria-risk function of population density, agricultural productivity function of technology and soil characteristics	not explicitly considered	no feedback
MERGE 2	market damage linear in consumption, non-market damage logistic in consumption per capita and linear in consumption	not explicitly considered	GDP, utility (in Pareto optimal run only)
MERGE 3	market damage linear in consumption, non-market damage logistic in consumption per capita and linear in consumption	not explicitly considered	GDP, utility (in Pareto optimal run only)
CETA	damage linear in GDP	not explicitly considered	damage subtracted from GDP
CETA (revised)	market damage linear in GDP, non-market damage linear in GDP and population	not explicitly considered	market damage subtracted from GDP, non-market damage reduces utility
IMAGE 2.1	topography, soil characteristics, agricultural demand function of population, GDP/capita, caloric intake/capita and desired diet, agricultural supply function of import/export and regional agricultural potential	land allocation (expansion/contraction and intensification/extensification)	land use feed into carbon cycle and influence albedo
CSERGE(M)	damage linear in GDP	not explicitly considered	no feedback
CSERGE(F)	damage linear in per capita income and population	not explicitly considered	no feedback
FUND 1.4	tangible damage linear in GDP, intangible damage quadratic in GDP, life and migration linear in population and per capita income	not explicitly considered	tangible damage subtracted from GDP; migration and mortality affect population size
FUND 1.5	tangible damage linear in GDP (agriculture linearly decreasing in GDP, linearly increasing in population), intangible damage linear in GDP and logistic in GDP/capita, life (valuation) and migration (valuation) linear in population and per capita income, migration and malaria logistic decreasing in per capita income, heat stress linear in urban population	only induced adaptation	tangible damage subtracted from consumption and investment; migration and mortality affect population size
PAGE 91	EU damage grows 3% per year, other regions presumable at same pace	policy variable; no induced adaptation	no feedback
PAGE 95	damage linear in GDP	policy variable; no induced adaptation	no feedback
MARIA	damage linear in GDP	not explicitly considered	GDP scaled down with damage
ICAM 2.0	market damage linear in GDP, non-market damage linear in GDP and logistic in per capita income	only induced adaptation	GDP, utility
ICAM 2.5	market damage linear in GDP; non-market damage linear in GDP and logistic in per capita income; sea level rise impacts linear in population density	only induced adaptation (with user-definable threshold)	GDP, utility
MiniCAM 2.0	complex	induced	market impacts subtracted from GDP
PGCAM	complex	induced	market impacts subtracted from GDP
DIAM	damage linear in GDP	not considered	no feedback
AS/ExM	damage linear in GDP	not considered	no feedback
FARM	population, labour, capital	production practices in agriculture and forestry; land, water, labour and capital allocation	consumption and trade patterns

ICAM, adaptation is driven by a stochastic signal. A few models include behaviourial rules (*IMAGE*, crop management practices in *FARM*) or optimization (*PAGE*, producers' and consumers' behaviour in *FARM*) to drive adaptation. These models are superior, also because they allow for adaptation capacity to depend on the socio-economic situation. None of the models include endogenous technological progress in adaptation capacity (research and development, learning by doing).

With a majority of IAMs representing damage in a highly aggregate, reduced form, few interesting feedback mechanisms can be expected (T4-4). Most commonly, damages are fed back simply by subtracting monetized market damage from output,[8] without reference to which or whose budget is restricted. Scheraga et al. [39] do discuss this using a dynamic, general equilibrium model. In some cases, non-market damages are also deducted from economic output, although such practice is strictly speaking incorrect (the effect it has on economic growth need not be large, though, cf. Tol [41]). Intangible effects do, by definition, not affect output and should therefore directly enter the welfare function. *FUND* is the only model that includes effects on population size and growth, noting that impacts on human morbidity and mortality will affect labour productivity and the size and growth of the population. *FARM* includes the effect of changes in land productivity on all sectors, and captures the effects of changes in one sector (particularly agriculture) on all other sectors.

The detailed analysis of climate change impacts on different sectors is often hindered by the low level of disaggregation in the socio-economic module of the IAMs, a feature which forestalls an analysis of higher order impacts, such as the effect of agricultural damage on other sectors of the economy (*FARM* is a distinct exception). Agriculture, although only a small economic activity in developed countries, delivers input to a large number of other sectors, which will thus be indirectly affected by global warming. Another example, coastal defence, may be viewed as a responsibility, even activity of the (national) government; sea level rise may thus cause an expansion of public spending or a cut of other government expenditures (e.g., health care, education).

The impact modules of "process-based" integrated assessment models tend to be more fully integrated with the physical components of the model (e.g., land use and carbon cycle), but the link to socio-economic components (if included) is generally very weak.

5. Conclusions

The current generation of IAMs displays a wide variety of different approaches. An important distinction can be drawn between policy evaluation models and policy optimization models. The former tend to be closer to the natural sciences. They tend to be descriptive and usually contain greater modeling detail. Impacts are displayed in great spatial detail, but without following political borders. Optimization models are normative in the sense that they strive to derive an "ideal" policy, usually as defined by economic theory. Optimization models are more likely to use reduced form representations of impact, and the regional disaggregation is generally according to broad geo-political boundaries. This diversity between models is a distinct advantage of integrated assessment, as no single model would be capable of answering all questions.

There is less modeling diversity within each of the above two categories, though. The impact modules of economics-oriented IAMs in particular tend to be based on a relatively small basis of sources, although there is a considerable variety in the interpretations of this material.

Integrated assessment models can only be as good as the literature on which they are based. Not least for this reason, the impact module remains the weakest link in many IAMs. This is particularly the case for those models that utilize monetized damage estimates as the basis of their assessment. IAMs describing impacts in physical terms tend to have much stronger impact modules. The advantage of monetization is that it makes it much easier to feed impacts back into the socio-economic module of the model. "Physical" IAMs rarely close the loop, not least because of the difficulties of integrating physical impact indicators into an economic model, where flows are commonly measured in monetary terms.

This potential advantage of monetized models is partly offset by the high degree of aggregation in the current generation of models, which makes it difficult to gain meaningful insights into the economy–damage interlinkage. Computational constraints permitting, IAMs should ideally model as many damage categories as possible separately, as each of them depends on socio-economic and climatic developments in a different way and may be interlinked with different parts of the IAM. At the very least, monetized models should distinguish between market based damages (which feed back into the economic system) and non-market impacts (which directly affect welfare). Given the difference in time profile, a separate treatment of sea level rise related impacts would also be desirable.

On the other hand, it has to be recognized that there is a clear tradeoff between modeling detail and the number of impact categories it is possible to include. For policy evaluation models, it may be argued that comprehensiveness is not of prime importance. There are clearly features of climate change that merit studying in great detail, and at the expense of ignoring the larger picture. Crucial interactions between impacts need of course to be taken into account. For optimization models, however, comprehensiveness would appear to be of utmost importance. The policy advise obtained from these models is likely to be biased unless all relevant impacts are duly included, to the extent this is possible at any particular time. Consumers of IAM results will have to be aware, however, that compre-

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[8] In some models, output is divided by the damage share; this is just a re-parameterization.

hensiveness has been achieved at the expense of some regional or impact-specific detail, information on which may have to be supplied by other sources.

Comparison of the impact modules of policy evaluation and optimization models is hampered by the radically different modeling approaches. It requires building an additional final "layer" to evaluation IAMs, and an additional intermediate layer to optimization IAMs. Besides, for model comparison purposes, such additional layers would be helpful for summarizing and interpreting impacts (evaluation IAMs) or for sensitivity and uncertainty analysis (optimization IAMs).

Impact research has for too long focused on the benchmark case of $2 \times CO_2$. To some extent, IAMs with their inherently transient structure now pay the price for this limited focus. Damage modules are often not more than ad hoc extrapolations around the $2 \times CO_2$ benchmark. Developing meaningful functional forms for time-dependent damage as a function of changing socio-economic circumstances, vulnerability, degree of adaptation, and the speed and absolute level of climate change is perhaps the main challenge facing IA modelers.

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