OECD Environment Working Papers No. 66

Integrated Assessment of Climate Change Impacts: Conceptual Frameworks, Modelling Approaches and Research Needs

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https://dx.doi.org/10.1787/5jz2qcjsrvzx-en

OECD

Unclassified **ENV/WKP(2014)3**

Organisation de Coopération et de Développement Économiques
Organisation for Economic Co-operation and Development **11-Jun-2014**

English - Or. English

ENVIRONMENT DIRECTORATE

ENV/WKP(2014)3
Unclassified

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INTEGRATED ASSESSMENT OF CLIMATE CHANGE IMPACTS: CONCEPTUAL FRAMEWORKS, MODELLING APPROACHES AND RESEARCH NEEDS

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JEL Classification: Q50, Q54, Q59

Keywords: climate change, climate impacts, adaptation, integrated assessment modelling

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JT03359120

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ABSTRACT

This paper presents a framework to include feedbacks from climate impacts on the economy in integrated assessment models. The proposed framework uses a production function approach, which links climate impacts to key variables and parameters used in the specification of economic activity. The key endpoints within climate impact categories are linked to the relevant connections for a range of sectors in the economy. The paper pays particular attention to the challenges of distinguishing between damages and the costs of adapting to climate change.

The paper also reviews existing studies and available data that can be used to establish linkages between climate impacts and key variables within economic models. There is considerable heterogeneity across the timing and geographic distribution of changes in climatic variables, the consequent changes in key physical and biogeochemical "endpoints" that might occur over time and space, and the magnitude of the resulting damages that these effects are likely to impose on the range of sectors in the economy. The review underlines the uncertainty involved in each of these dimensions and the research needs for the future.

Keywords: climate change, climate impacts, adaptation, integrated assessment modelling

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RESUMÉ

Le présent document expose une méthodologie visant à inclure, de façon systématique, les effets économiques consécutifs aux impacts du changement climatique dans les modèles d'évaluation intégrée. La méthode proposée se fonde sur le concept de la fonction de production, en reliant les différents impacts environnementaux associé au changement climatiques à leurs effets sur les variables et les paramètres clés des modèles utilisées pour décrire les mécanismes et interactions économiques. Il s'agit d'associer les principaux impacts environnementaux aux différentes activités économiques qu'ils sont appelés à impacter. Le document accorde une attention particulière à la difficulté de distinguer les coûts de l'adaptation au changement climatique des dégâts dus à ce changement.

Le document passe également en revue les études existantes ainsi que les données disponibles qui peuvent être utilisées pour établir des liens entre les impacts climatiques et les variables clés dans les modèles économiques. Cette revue de littérature souligne les très fortes disparités spatiales et chronologiques des modifications environnementales dues au changement climatique, et par conséquent une forte hétérogénéité que ces impacts physiques et biogéochimiques sont susceptibles de poser à l'ensemble des secteurs de l'économie, tant dans leur amplitude que sur le plan géographique ou temporel. L'analyse souligne l'incertitude liée à chacune de ces dimensions et les besoins de la recherche pour l'avenir.

Mots clés: changement climatique, impacts des changements climatiques, adaptation, modélisation de l'évaluation intégrée

Classification JEL: Q50, Q54, Q59

FOREWORD

This report on "Integrated assessment of climate change impacts: conceptual frameworks, modelling approaches and research needs" has been prepared as a background for modelling climate impacts within the OECD CIRCLE project. The report provides a background for modelling climate change impacts in economic models that can be used for integrated assessment of climate change. The report outlines the state-of-the-art framework for the modelling of the economic implications of climate change impacts, with additional focus on adaptation to climate change. It also reviews the main literature that can be relevant to model climate impacts with regard to both methodology and results from applied studies.

This report has been authored by Ian Sue Wing, Associate Professor, Department of Earth & Environment, Boston University and Elisa Lanzi, OECD Environment Directorate. The preparation of the report has been overseen by Rob Dellink of the OECD Environment Directorate. The paper has benefitted from comments received by the technical experts and academics at the ad-hoc technical workshop on the CIRCLE project, 21-22 October 2013. It was then submitted to EPOC for declassification under the written procedure and declassified after incorporation of all comments received. Comments and suggestions from Shardul Agrawala, Jean Chateau, Ada Ignaciuk, Helen Mountford and Simon Upton of the OECD are gratefully acknowledged.

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1. Introduction

1. The continuing rise in global emissions and atmospheric concentrations of greenhouse gases (GHGs) has led to mounting concern over potentially adverse impacts of future climate change on natural and human systems. Quantifying the economic costs of climate impacts is extremely challenging. Impacts exhibit considerable heterogeneity across multiple dimensions: the timing and geographic distribution of changes in climatic variables, the consequent changes in key physical and biogeochemical "endpoints" that might occur over time and space, and the magnitude of the resulting damages that these effects are likely to impose on the range of sectors in the economy. Each of these dimensions is subject to uncertainty, and is the focus of different analytical frameworks that utilize computational simulation models. To undertake integrated assessments of climate impacts these modelling components need to be streamlined and the interfaces between them articulated and coordinated.

2. The purpose of this review is twofold, to provide a critical summary of the state of knowledge in this area, and to develop insights for modelling both the endpoints in different impact categories and their connections to economic activities as represented within integrated assessment models (IAMs).

3. The report analyses the meaning of "damage" in the context of climate impacts, paying particular attention to the challenges of distinguishing between damages and the costs of adapting to climate-induced shocks to the economy. These elements are then combined to develop a canonical integrated assessment (IA) framework, which is used throughout the report. Building on this framework, the report identifies and classifies the key economically relevant impacts of climate change. It then enumerates both key endpoints within these impact categories and the relevant connections with a range of sectors in the economy. Finally, it outlines options for representing these connections as shocks within economic simulations, and briefly summarizes key data and research needs for establishing backward linkages between these shocks and changes in climate variables.

4. The remaining sections of this report are organized as follows. Section 2 begins by outlining the conceptual framework for assessing climate impacts and human adaptation to them, developing a general taxonomy of the economic effects that can potentially arise Section 3 dissects the ways in which this framework has been operationalized through a critical examination of existing modelling approaches and a brief survey of their results, from which tentative implications are drawn. Section 4 provides an in-depth analysis of critical implementation issues in modelling the costs of climate impacts. Section 5 concludes with a summary of the main points.

2. Conceptual Frameworks

2.1 Integrated Assessment of Climate Impacts

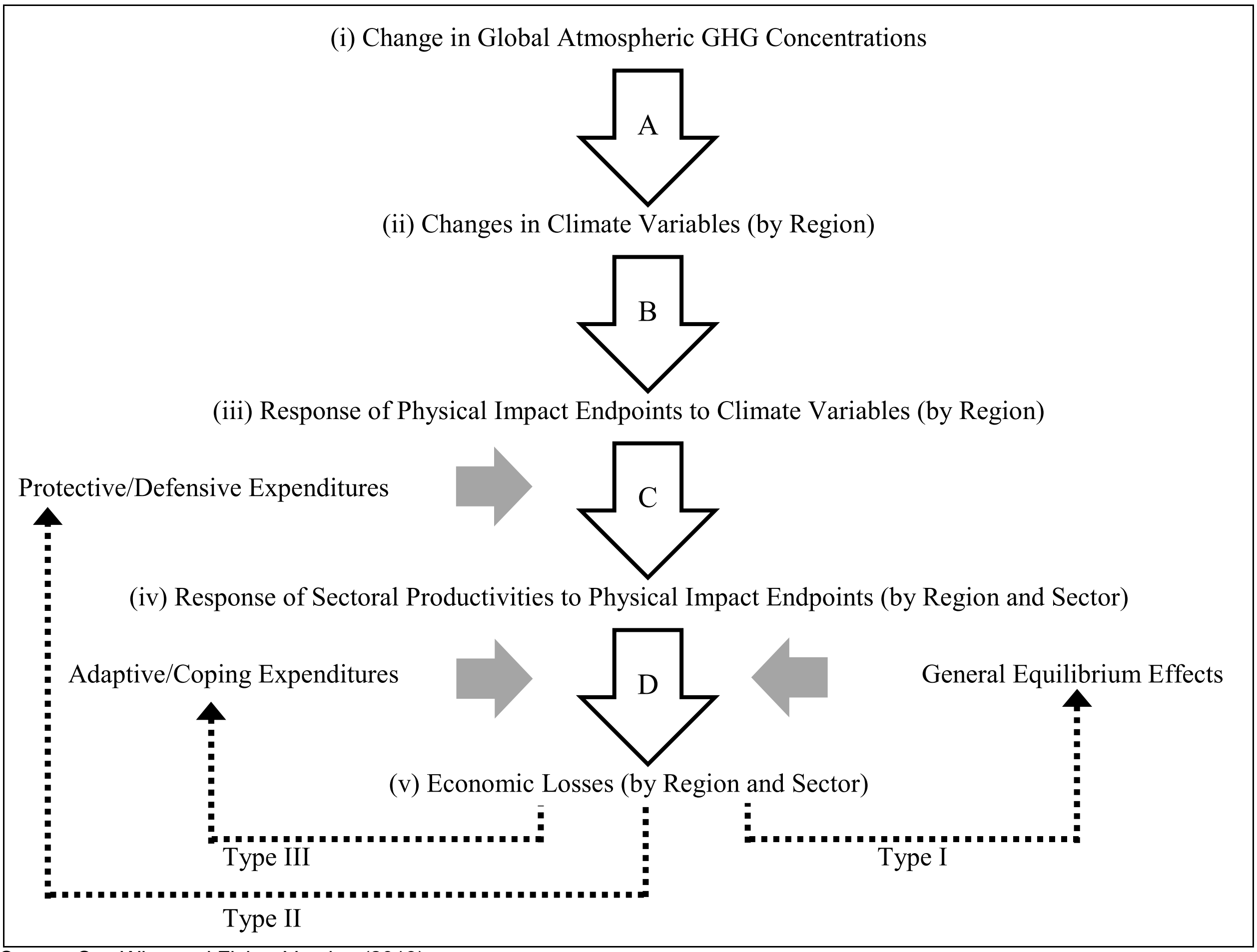
5. This section introduces conceptual frameworks for understanding the origins of, and key uncertainties associated with, impacts of climate change. Sue Wing and Fisher-Vanden (2013) outline a particularly useful approach, which is illustrated schematically in Figure 1. Starting from the top of the diagram, human-induced increases in atmospheric GHG concentrations (i) drive changes in climate variables such as temperature and precipitation at the regional scale (ii). These climatic changes result in physical and biogeochemical impacts (iii) which influence the productivity of various sectors of the regional economies where the impacts occur (iv), and ultimately give rise to economic losses (v).

6. The chain of influences (A)-(D) that connects these components is at the core of the integrated assessment (IA) methodology. Vertically IAMs may combine representations of some or all of the following components: the determinants of socioeconomic development, emissions caused by economic growth, the atmosphere-ocean-climate system, ecosystems, socioeconomic impacts, mitigation and

adaptation policies and associated economic responses, with different types of models emphasizing different linkages (Parsons and Fisher-Vanden, 1997).

7. There are various sources of uncertainty in the IAM process, including future economic growth, the level of emissions that will be linked to economic activities, the link between emissions and global temperature and the regional impacts that the temperature change will lead to. A critical first-order uncertainty is the effect of global atmospheric GHG concentrations on radiative forcing which drive changes in global mean temperature, and, in turn, shifts in climate variables at finer spatial scales. In climate simulations this response is captured by the equilibrium climate sensitivity (ECS) and—especially for high-warming scenarios—the transient climate response (TCR).[1] Likely ranges ECS and TCR are 2-4.5°C and 1.2-2.6°C, respectively (IPCC, 2013b), and these are spanned by the latest round of global climate model (GCM) intercomparisons (CMIP5). In the highest warming scenario considered by the IPCC 5th Assessment Report (IPCC, 2013a) these uncertainties led to change in global mean temperature relative to preindustrial levels in the range 4-6.1°C by 2100.

Figure 1. Economic damages from climate impacts: a bottom-up framework



Source: Sue Wing and Fisher-Vanden (2013)

[1] ECS is the equilibrium change in global surface temperature from doubling of the atmospheric equivalent CO_2 concentration, while TCR is the change in global surface temperature from a 1% per year increase in atmospheric equivalent CO_2 at the time of GHG doubling.

8. Downstream of global mean temperature, conceptual and computational exigencies in simulating these various components in an integrated fashion force a trade-off between modelling the breadth of system components and linkages and capturing the depth of within-component detail. Chaining together different dedicated models for the purposes of assessment can be prohibitively time-consuming, in addition to requiring substantial effort to translate detailed descriptors of the state of natural systems into shocks that affect economic activity. The tendency has therefore been to specify IAMs' internal components in ways that are simplified and highly aggregated along multiple dimensions, with consequent limits on their ability to resolve key aspects of climate impacts' effects on natural and human systems and the interactions between them - both within and across regional borders (e.g., in the case of international trade).

9. A key challenge is to adequately capture the dimensionality and heterogeneity of climate change impact endpoints' attributes, geographic occurrence, and response to shifts in climate variables (linkage B in Figure 1). Another difficulty is to capture how endpoints' effects on natural and human systems vary in character and magnitude across regions, and how these influences translate into shocks to the economy, with some activities or sectors being more severely affected than others, through the channels of different (and potentially multiple) economic variables (linkage C).

10. Along the time dimension, IAMs typically solve on time-steps of one year to decades, which makes it difficult to capture short-duration extreme weather events (e.g., storms, floods or droughts), their short-run effects on the economy, and longer-run persistent impacts induced by them. As well, the vast majority of IAMs step through time in a myopic fashion, as full intertemporal solution of the economic growth, GHG emissions, climate change impacts and damage relationship is computationally intractable for all but a small number of regions, time periods and impact categories - which is the particular dimension of concern here. Consequently, forward-looking simulations of the DICE/RICE variety (Nordhaus and Boyer, 2000; Nordhaus, 2009; Nordhaus et al., 2010; de Bruin et al., 2009; Bosello et al., 2010b) are able to trade off the ability to adjust emissions and economic growth in anticipation of economic losses due to the impacts of future climate change.

11. The trade-off is that such functionality comes at the cost of a highly simplified representation of the climate system and the damage from impacts associated with increases in global mean temperature. Moreover, the strength of the anticipatory response is governed by the assumed rate at which economic actors discount the future. Even in myopic projections of climate impacts, discounting is the primary determinant of aggregated future damages, and for this reason highly controversial (see IPCC, 2014). With a sufficiently high discount rate, even catastrophic losses that substantially reduce gross world product at the time of their occurrence will appear small in present value terms if the corresponding impacts occur far in the future (Weitzman, 2007; Stern, 2008; NRC 2010; IPCC, 2014). This has led analysts to explore alternatives to the standard geometric discounting method (e.g., hyperbolic or gamma discounting). But these considerations should not diminish the fact that what makes discounting important for cost-benefit accounting is the uncertain timing and magnitude of climate damages that arise over very long time horizons, which in turn depend critically on the substantive questions of what impacts will manifest themselves, in what ways, and with what economic effects. The latter points are fundamental, and are the focus of the remainder of the report.

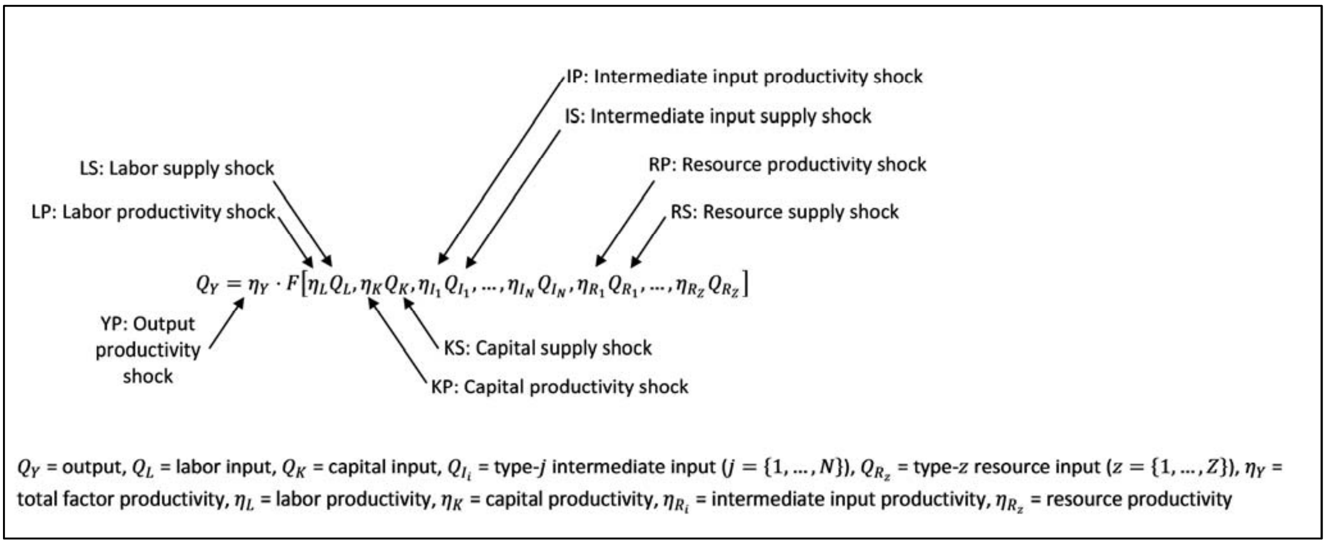
12. In geographic space, IAMs divide the world into a relatively small number of regions, each of which tends to be treated in a more or less homogeneous fashion despite its large extent. The difficulty is then capturing the geographic specificity of exposure and vulnerability. For example, if a certain climate impact affects individual countries in the same region in opposite ways, the individual effects tend to cancel out, resulting in an aggregate regional-level impact that is deceptively small. Symmetrically, in addressing the common problem of missing data on interregional differences in exposure or vulnerability to a particular impact, often the only workaround is to first model how the impact's losses vary with socioeconomic variables (e.g., income), and then use the resulting response surface to distribute costs

among regions. In these sorts of procedures the costs associated with multiple endpoints tend to be aggregated together, even though different endpoints may vary with income in dissimilar ways, and, more fundamentally, exposure is also likely to vary spatially. Finally, the way in which IAMs represent economic activity tends to be highly aggregated, with individual industries often grouped into a relatively small number of sectors. This too can lead to problems of aggregation bias if an impact endpoint exerts differential economic effects on industries within the same coarse sectoral grouping.

13. Addressing the challenges described above requires a scoping analysis to identify impact endpoints — element (iii) in Figure 1 — followed by a two-track strategy. From this starting point, one can improve articulation of the forward linkages (C) by elaborating the interfaces between different endpoints and the economic sectors within IAMs. Articulation of the backward linkages (B) can be improved by developing empirically-based specifications of the responses of endpoints to changes in climate variables in different locales. The focus of this report will be to outline in detail the steps involved in pursuing the first track, however doing so impinges on many elements of the second track, which will also be discussed.

14. To pursue the first track, it is necessary to sort the myriad channels through which impact endpoints translate into shocks to the economy and to study how the economy responds to these shocks (linkage D in Figure 1). The diagram in Figure 2 provides a useful conceptual framework.

Figure 2. Modelling climate impacts: a production function approach



Source: authors drawing on the GCE modelling literature.

15. The core of this framework is a production function, which is the standard algebraic representation of the activity of an industry or group of industries in the economy, and widely used by IAMs. Output (variable Q_Y) is produced from h distinct inputs - labour, capital, j categories of intermediate commodity inputs and z categories of primary resources (variables Q_L, Q_K, Q_{I_j}, and Q_{R_z}) - according to a production technology (function $F[\cdot]$). In this abstract setting, F defines the envelope of possibilities available to producers for substituting inputs at any instant of time. Technical change is the force which shifts and contorts this envelope, effects which are represented in parametric form by technological augmentation factors (η). The shift parameter η_Y captures the effect of neutral technological change that equiproportionally shifts the productivity of all inputs while keeping substitution possibilities the same. The parameters η_L, η_K, η_I and η_R capture the effect of biased technological change, which increases or decreases the productivity of different inputs at different rates, thereby shifting substitution possibilities in

different directions. Such changes are important because they feed back on producers' inputs demands and output supplies, which in turn lead to shifts in the equilibria in markets for factors and commodities.[2]

16. Climate endpoints have the potential to directly affect sectors' use of labour, capital, intermediate inputs and resources (denoted *LS*, *KS*, *IS* and *RS*, respectively). Concern centres on the adverse effects of climate impacts on input supplies, particularly the loss of the economy's endowments of primary factors such as labour, capital, land and natural resources.[3] Nevertheless, current understanding of various categories of impacts suggests that such effects may be the exception rather than the rule. The characteristics of impacts considered in subsequent sections make it appear far more likely that climate endpoints will affect the productivity of inputs to production - either differentially, denoted *LP*, *KP*, *IP* and *RP*, or in a neutral fashion, denoted by *YP*. Adverse climate-related shocks to the economy therefore act in the same manner as technological retrogressions, necessitating the use of more inputs to generate a given level of output (*LP*, *KP*, *IP*, *RP*, *YP* < 1). However, the fact that the majority of impact categories can be conceptualized and/or represented as productivity declines does not imply that supply-driven shocks are small in magnitude, or should be ignored. What impact end up being more consequential to economic well-being is very much an empirical question.

2.2 Understanding "Climate Damages": the Critical Role of Adaptation

17. Having catalogued the types of economic shocks that climate change impact endpoints can generate, the next task is to establish how economic damages arise out of their effects. To frame the issue, consider a simplified version of the production function in Figure 2 which represents the production process of not just an individual sector but the entire economy. In this "value added" production function there are no intermediate commodity inputs, Q_Y represents the economy's output or GDP, and Q_L, Q_K and Q_R represent aggregate endowments of non-reproducible primary factors. Faced with a lack of information about the linkages between changes in impact endpoints and the productivity of various sectors, or the inputs thereto, a convenient assumption is that the impacts' adverse effects on individual sectors can be aggregated together and expressed as a shock to GDP. This is easily modelled by imposing a reduction in the value of the neutral technology shift parameter η_Y, which results in a decline in Q_Y with fixed usage of the economy's factor endowments.[4] This is the approach taken by the DICE family of models (Nordhaus and Boyer, 2000; Nordhaus, 2009), which specify climate-induced changes in η_Y using the device of an aggregated damage function based on global mean temperature change. Climate damages can then be quantified simply as the percentage change in η_Y multiplied by the baseline level of output which would have prevailed in the absence of climate change.[5]

18. However, once endpoints' differential effects on inputs are elaborated, the direct equivalence between climate-driven productivity shifts and changes in aggregate output is lost. It becomes necessary to translate the former into latter, which means using the production function to simulate output changes. This raises the thorny issue of distinguishing between the damage from climate impacts and the costs of adaptation to them, something which has not been forcefully emphasized in either the modelling or policy literatures (Bosello et al., 2010b). In the aggregated model sketched in the previous paragraph no adaptation occurs in the short run, in which factors are in perfectly inelastic supply under the full-employment assumption. The implication is that measures to lessen the impacts of climate change on the

[2] The next section highlights how these types of general equilibrium adjustments are central to the economic impact of climate change.

[3] An example is loss of coastal land, buildings and infrastructure due to inundation as a result of sea level rise.

[4] To keep the model simple, biased technological change is ruled out by the constraint $\eta_L = \eta_K = \eta_R = 1$. The resulting production function is $Q_Y = \eta_Y \cdot F[Q_L, Q_K, Q_{R_1}, \dots, Q_{R_Z}]$.

[5] See Stern (2013) for a critique of this approach.

economy must be explicitly included as attenuating factors that diminish the magnitude of the neutral shock.[6] By contrast, in the sector-level model in Figure 2 input supplies always exhibit some short-run elasticity, so a change in the productivity of a particular input, for example η_L, will trigger substitution responses by producers that alter not only their use of labour but uses of other inputs as well. The result will be changes in the input quantities Q_L, Q_K, Q_{I_i}, and Q_{R_z}, all of which combine with the change in η_L to generate a change in output. The fundamental point is that substitution is a form of adaptation once the level of the economy at which impacts manifest themselves is reached. Consequently, IAMs that employ input-based accounting for the effects of impact endpoints will tend to generate cost estimates that include the moderating effects of adaptation.

19. To understand the implications, consider two thought experiments. First, imagine that a climate shock to a particular sector of the economy is imposed in two IAMs that are identical in all but one respect: one of the models has a larger elasticity of substitution in the target sector. Economic costs simulated by the more flexible model will be smaller because of producers' ability to adjust more elastically to the shock, with smaller consequent relative price changes and general equilibrium effects. Second, imagine that the two models have identical substitution elasticities, but one represents the rest of the economy outside the impacted sector in a less detailed fashion. In this case what the finer-resolution model would resolve as individual activities, the more aggregated model treats as homogeneous perfect substitutes. The upshot is that in the latter economy the elasticity of substitution is implicitly larger within as well as outside the impacted sector, leading more elastic response to the shock, smaller general equilibrium effects, and lower costs. In both experiments the key unobservable is what the ex-ante or counterfactual damage would have been in the absence of adaptation. Ex post, the "direct cost" is the net residual reduction in output once adaptation measures have been implemented.

20. Other adaptation responses in addition to substitution are also possible. Indeed, adaptation is a portfolio optimization problem in which the selection of measures is governed by their relative marginal costs and marginal benefits, and the latter depend on expectations of impact endpoints' magnitudes and the exposure and vulnerability of the potentially impacted sectors and regions. Sue Wing and Fisher-Vanden (2013) identify three classes of responses: (I) passive general market reactions (e.g., shifting heating and cooling expenditures or choice of tourism destinations); (II) deliberate shielding investments (e.g., coastal protection infrastructure to defend against rising seas, or the development of drought- and heat-tolerant varieties of staple crops); and (III) deliberate coping investments (e.g., insurance, redundant or flexible production capacity, or investments in disaster preparedness, response and recovery). Type II adaptations reduce activities' exposure to risks associated with impact endpoints, and include investments that may be forward looking, as with infrastructure, or contemporaneous expenditures. A qualitatively different type of adaptation is Type III measures, which soften the adverse effects of residual impacts that shielding measures fail to prevent. These too can be proactive or reactive. Further, both Type II and Type III expenditures generally include a mix of public and private spending. Total costs are then the sum of Type II and Type III adaptation expenditures in addition to the residual losses of economic output discussed in the previous paragraph.

21. Attempts to elaborate the effects of impact endpoints on the inputs to production will inevitably blur the distinction between damage and the costs of adaptation, as estimates of the former unavoidably encompass costs or forgone output associated with Type I passive adaptations. Table 1 provides a summary of existing IAM studies of climate impacts, the majority of which focus on a few impact categories in isolation. Consistent with Figure 2, the partial-equilibrium and CGE modelling studies cited in the table simulate the endogenous market responses to climate-induced changes in productivity and primary factor supplies. The ultimate effects of the resulting shocks on GDP therefore include the

[6] Over the long run diminished output leads to reductions in the quantity of investment and slower growth of the capital stock.

moderating effects of substitution. Depending on the nature of the climate impact and the time-horizon considered by the analysis, published damage estimates also incorporate the additional cost of proactive or reactive Type II and III adaptations. Such adaptations generally give rise to savings by reducing the magnitude of direct damage, but these savings are purchased with offsetting increases in adaptation expenditure. Because of the computational intractability of capturing the necessary detail within intertemporal optimization models, proactive adaptation tends to be imposed upon models in the form of exogenous scenarios.

2.3 Core Elements of a Canonical Assessment Framework

22. For a future target year an ideal IA modelling framework would calculate the effect of a given level of global radiative forcing on climate variables at regional scales, the consequent region-specific changes in different categories of impacts, the effects of these endpoints on the various sectors of the economy, and the ultimate consequences for output, prices, and economic welfare costs. More formally, a fully flexible modelling framework would therefore capture impacts' effects through the interaction of four multiplicative influences: (A) the response of m climate variables in each of ℓ regions to accumulating atmospheric GHGs (or radiative forcing); (B) the ways in which these climatic changes drive each of i types of biophysical impact endpoints; (C) the effects of these endpoints on supply or productivity in each of j economic sectors in the region, either directly through the output channel or indirectly by affecting the h inputs; and finally, (D) the response of sectors' marginal cost and output to these shocks.

23. This framework may be operationalized by using a sequence of dedicated large-scale models.[7] Alternatively, the traditional IA modelling approach is to develop reduced-form representations of each component, chain them together and simulate them in a single step. Following the analysis in Sue Wing and Fisher-Vanden (2013), Table 2 outlines how the aforementioned influences may be expressed in the form of elasticities, which are a convenient way of normalizing the responses of otherwise incommensurate system variables to one another. The first panel elaborates the links in the causal chain A-D, while the second elaborates the influences of Type II and Type III adaptations. Sue Wing and Fisher-Vanden (2013) emphasize that each of these elements should be thought of as an endogenous variable as opposed to a fixed parameter. In particular, the elasticities of the responses can themselves vary according to functional relationships denominated over the variables identified in the third column of the table: the values taken on by the climatic variables, endpoint variables, levels of sectoral productivity output and unit cost.

24. The second panel distinguishes between adaptation measures that are contemporaneous in nature and result from cumulative actions to create a stock of adaptive capacity. This difference is critical for modelling, as the incentives to make near-term investments in the latter dynamic category are a function of expectations about the timing, location and sectoral exposure of future impacts. For example, large-scale engineering projects to harden coastal defences will be sited in locations where settlements face inundation risks from sea-level rise or more severe storms, with the rate of infrastructure investment determined by forecasts of the timing and magnitude of exposure. Here too, elasticities can capture the efficacy of these investments, but as before, the reduced-form representations are functions denominated over the magnitude of the relevant impact endpoints and the size of the relevant stock or flow in each category of adaptation spending. The bigger implication is that representing proactive adaptation requires models to simulate intertemporal decision making under uncertainty. The challenge is that this can only be achieved at a high computational cost, which has prevented intertemporal IAMs from elaborating detail simultaneously along regional, sectoral and impact category dimensions (cf. Agrawala et al., 2011).

[7] For example, assessment of agricultural impacts proceeds by using (1) GCM-derived fields of future changes in temperature and precipitation to calculate (2) changes in yields of particular crops in different locations, which can then be imposed as (3) productivity shocks to land in crop sectors in an IAM, whose production functions translate them into (4) changes in output and costs.

Table 1. Recent IAM studies of the economic consequences of climate impacts

Study	Regional scope	Sectoral focus	Remarks
Global intertemporal economic modelling studies			
de Bruin et al. (2009)	Global	Aggregate	Uses AD-DICE/AD-RICE model (global damage function)
Bosello et al. (2010b)	Global (12 regions)	Aggregate with energy system detail	Uses AD-WITCH model (global damage function)
Nordhaus et al. (2010)	Global (12 regions)	Aggregate	Uses RICE-2010 model (regional damage functions)
CGE economic modelling studies			
Deke et al. (2001)	Global (11 regions)	Agriculture, Sea-level rise	Uses DART model (Klepper et al., 2003)
Darwin (1999)	Global (8 regions)	Agriculture	Uses FARM model (Darwin et al., 1995)
Darwin and Tol (2001)		Sea level rise	
Jorgenson et al. (2004)	U.S.	Agriculture, Forestry, Energy, Water, Coastal protection, Air quality, Heat stress	Uses IGEM model (Jorgenson and Wilcoxen, 1993)
Bosello et al. (2005)	Global (8 regions)	Health	Uses GTAP-EF model (Roson, 2003)
Bosello and Zhang (2006)		Agriculture	
Bosello et al. (2007a)		Energy demand	
Bosello et al. (2007b)		Sea level rise	
Berittella et al. (2006), Bigano et al. (2008)	Global (8 regions)	Tourism, Sea level rise	Couples HTM and GTAP-EF models
Eboli et al. (2010)	Global (14 regions)	Agriculture, Tourism, Energy demand, Sea level rise, Health	Uses ICES model
Bosello et al. (2010a)	Global (14 regions)		Couples AD-WITCH and ICES models to investigate adaptation
Bosello et al. (2011)	Europe (3 regions)	Ecosystem services, linkages to 5 impact sectors in Eboli et al. (2010)	Uses ICES model
Bosello et al. (2012a,b)	Global (14 regions)	Agriculture, Forestry, Tourism, Energy demand, Sea level rise, Health, Flooding	Uses ICES model
Ciscar et al. (2009, 2011, 2012)	Europe (5 regions)	Agriculture, Sea-level rise, Flooding, Tourism	Uses GEM-E3 model (Capros et al., 1997)
Calzadilla et al. (2010)	Global (16 regions)	Water Resources, Agriculture	Uses GTAP-W model (Berrittella et al. 2008)
Reilly et al. (2012)	Global (16 regions)	Agriculture, Health, Ecosystems	Uses MIT EPPA model (Paltsev et al., 2005)
Literature surveys			
Agrawala and Fankhauser (2008)	Multiple regions	Coastal zone, Agriculture, Water resources, Energy demand, Infrastructure, Tourism, Health	Survey of studies providing sector-specific estimates of adaptation costs generated by sectoral economic simulations
World Bank (2010)	6 developing regions	Infrastructure, Coastal zones, Water supply and flood protection, Agriculture, Fisheries, Health, Extreme weather events	Sector-specific estimates of adaptation costs, generated by combining dose-response functions with engineering analyses and sectoral economic simulations
UNFCCC (2007)	Asia, Latin America, Africa, Small island states	Agriculture, Water resources, Health, Terrestrial ecosystems, Coastal zones	Summarizes vulnerability, current and future adaptation plans/strategies, drawing on UNFCCC national communications, regional workshops, expert meetings.
Agrawala and Fankhauser (2008)	Multiple regions	Coastal zone, Agriculture, Water resources, Energy demand, Infrastructure, Tourism, Health	Survey of studies providing sector-specific estimates of adaptation costs generated by sectoral economic simulations
World Bank (2010)	6 developing regions	Infrastructure, Coastal zones, Water supply and flood protection, Agriculture, Fisheries, Health, Extreme weather events	Sector-specific estimates of adaptation costs, generated by combining dose-response functions with engineering analyses and sectoral economic simulations
Sectoral partial equilibrium studies			
Block et al. (2008)	Ethiopia	Water, Agriculture	Uses IMPACT model (Rosegrant et al., 2008)
Nelson et al. (2008)	Global (281 regions)	Water, Agriculture	
Butt et al. (2005, 2006)	Mali	Agriculture	Uses MASM model

Atwood et al. (2005, 2006)	U.S. regional	Agriculture	Uses ASM model (McCarl et al., 1998)
McCarl et al. (2000)	U.S.	Forestry	Uses FASOM model (Adams et al., 1996)
Sohngen et al. (2001)	Global (9 regions)	Forestry	Uses an optimal control model (Adams et al., 1996)
Other Simulation Studies			
Tol (2008)	Global (16 regions)	Health	Uses FUND model (Tol, 1995; Anthoff and Tol, 2008) which has regional damage functions for impact end-points (species loss, agriculture, coastal protection, disease morbidity/mortality, cyclones, migration, ecosystems, sea-level rise).
Tol (2007), Nicholls et al. (2008)		Sea level rise	
Narita et al. (2010)		Cyclones	
Link et al. (2004)		Multisector	
Hope (2006)	Global (8 regions)	Aggregate	Uses PAGE model (Plambeck and Hope, 1996)

Source: Adapted from Fisher-Vanden et al. (2013)

Table 2. Key elasticities in modelling climate impacts and adaptation

Name*	Description	Functional Dependencies
A. Impacts		
Radiative forcing elasticity of local climate variables [A]	Elasticity of climate variable m in region ℓ with respect to the global atmospheric concentration of GHGs	Value of the mth climate variable in region ℓ Atmospheric stock of GHGs
Climate elasticity of impact endpoints [B]	Elasticity of the ith biophysical endpoint in region ℓ with respect to the mth climate variable	Magnitudes of the i impact endpoints in region ℓ Values of the m climate variables in region ℓ
Endpoint elasticity of sectoral productivity [C]	Elasticity of the shock to the output productivity of the jth sector in region ℓ with respect to the ith impact endpoint Elasticity of the shock to the productivity of the hth input to the jth sector in region ℓ with respect to the ith impact endpoint	Magnitude of the ith endpoint in region ℓ Output productivity level of the jth sector in region ℓ Productivity level of the hth input to the jth sector in region ℓ
Productivity elasticity of sectoral output [D]	Elasticity of output/marginal cost of the jth sector in region ℓ with respect to climate-induced productivity shocks	Production/cost function structure and parameters General equilibrium influences
B. Adaptation		
Reactive shielding adaptation elasticity	Elasticity of the shock to the productivity of the jth sector in region ℓ from the ith impact endpoint with respect to reactive Type II adaptation investment	Magnitude of the ith impact endpoint in region ℓ Adaptation investment targeted at the ith impact endpoint's effects on the jth sector in region ℓ
Reactive coping elasticity	Elasticity of the ith impact endpoint's shock to productivity in the jth sector in region ℓ with respect to reactive Type III adaptation investment	Magnitude of the ith endpoint's shock to the productivity of the jth sector in region ℓ Adaptation investment targeted at the ith impact endpoint's effects on the jth sector in region ℓ
Proactive shielding elasticity	Elasticity of the jth sector in region ℓ's exposure to the ith impact endpoint with respect to the stock of proactive Type II adaptation capacity	Magnitude of the ith endpoint in region ℓ Level of adaptation capacity targeted at the effects of the ith impact endpoint on the jth sector in region ℓ
Proactive coping elasticity	Elasticity of the ith endpoint's shock to productivity in the jth sector in region ℓ with respect to the stock of proactive Type III adaptation capacity	Magnitude of the ith endpoint's shock to the productivity of the jth sector in region ℓ Level of adaptation capacity targeted at the effects of the ith impact endpoint on the jth sector in region ℓ

Source: Adapted from Sue Wing and Fisher-Vanden (2012).
*Letters in square brackets correspond to the linkages in Figure 1.

25. In line with the emphasis on modelling, the rest of this report elaborates the linkages among endpoints (i), economic sectors (j), and their various constituent inputs (h), but leaves aside explicit consideration of the geographic coverage in these linkages (ℓ). This is an important limitation in light of the fact across much of the globe the pervasive absence of historical measurements of endpoints, their consequences, and, crucially, their responses to the influence of climate variables, is the biggest obstacle to progress in climate impacts research. Improvements in the availability of the outputs of global climate model (GCM) runs now make it much easier to assess the exposure of different regions to scenarios of change in climatic variables. However, translating these shifts into changes in a particular impact endpoint requires at least a reduced-form characterization of climate change-endpoint linkage, which turns out to be a key area of interest in the empirical economics literature.[8]

26. Empirically-estimated reduced-form relationships have great potential to contribute to the construction of shocks in various impact categories, but if they are to be used to fill geographic data gaps the key question is whether they are sufficiently generic. In an ideal world, reduced-form climate response functions for a particular endpoint would be estimated using historical observations from the regions where these data are available, controlling for several confounding factors, not the least of which are location-specific effects and adaptation to past climatic change. The resulting climate-endpoint relationships which are purged of other influences could then be combined with the outputs of GCM simulations of future warming scenarios—especially in regions lacking historical endpoint data - as a way to potentially impute the global pattern of changes for the endpoint in question. The first step in operationalizing such a strategy is to compile a detailed inventory of data gaps, something which is beyond the scope of this review. Nevertheless, the discussions in Section 4 will sketch the outlines of both the constraints on data availability and potential workarounds, and as far as possible identify sources of relevant historical data.

3. Implications for Integrated Assessment Modelling

3.1 Implementing the Canonical Framework: Progress of Existing Methodologies

27. The studies in Table 1 have made limited progress towards the ideals in Section 2.3. In terms of linkage (A), IAMs are still struggling to move beyond global mean temperature change as a sufficient statistic for representing local changes in meteorological variables. Two key stumbling blocks have proved challenging to circumvent. The first is the lack of computationally efficient reduced-form emulators of global climate simulations that are capable of modelling region-specific changes in climate variables (e.g. temperature, precipitation and sea level rise) as functions of different degrees of global warming.[9] The second is the lack of empirically grounded regional-scale impact response functions to translate local changes in climate into changes in impact endpoints and shocks to economic sectors.[10] Without these fundamental physical connections at regional scales, the alternative has been to specify regional impact endpoints directly in response to global mean temperature, as for example in the FUND model (Tol et al., 1995; Tol, 1995; Anthoff and Tol, 2008). But such a workaround is problematic as the paucity of data constrains FUND's internal relationships to be specified more on the basis of expert judgment and assumptions than rigorous empirical analysis. The upshot is an inability to unpack - or characterize the effects of - the considerable multiplicative uncertainty in the causal chain from radiative forcing to local climate to impact endpoints to economic shocks.

[8] For reviews see Olmstead (2012), Auffhammer and Mansur (2012), Auffhammer and Schlenker (2012), Klaiber (2012), Kousky (2012) and Deschenes (2012).

[9] Codes such as COSMIC2 (Schlesinger and Malyshev, 2001) and MAGICC ScenGen (Wigley, 2008) have made some progress in this regard by scaling the patterns of local climate from different GCMs, but still lack the necessary flexibility.

[10] Table 4 in Annex I reviews possible approaches to include climate impacts in CGE models for different sectors.

28. These limitations, as well as increased availability of spatially-resolved outputs of GCM simulations, have led to increased efforts to chain together the outputs of different dedicated modelling platforms. In the typical procedure, GCM results are used to force impact models at the regional scale, and the resulting impact endpoints are translated into shocks that are then imposed in multi-region, multi-sector IAMs (e.g., Ciscar et al., 2011). Challenges abound, however. A fundamental constraint is that regional climate changes, and their consequent impacts and economic costs, are both tied to the particular scenario of warming used to force the GCM run, with corresponding lock-in to scenario-specific temporal and geographic patterns of change. For this reason considerable attention is being focused on methods to translate GCM outputs into "phase space" as a way of moving toward the more flexible elasticity-based representation advanced above. In particular, specification of linkage (A) turns on the ability to express the spatial patterns of climatic shifts as functions of the models' own simulated global mean temperature change. An additional drawback is the computational and time cost of having to simulate engineering or natural science process models in every instance that new spatial or temporal fields of impacts need to be generated to force IAMs. Especially where process simulations run at fine spatial and temporal scales, it can be prohibitively time-consuming to conduct analyses spanning multiple scenarios in many regions over long time-horizons. Thus, here too there is interest in constructing computationally efficient reduced-form response surface analogues of process models, consistent with the elasticities reflected in factor (2).

29. Fortunately, tentative steps toward bridging the latter disconnect have gotten under way. The 2012 "Integrated Assessment Modelling" workshop hosted by the US National Bureau of Economic Research brought together empirical economists and IA modellers studying climate change impacts and adaptation in six areas: extreme events/sea level rise; water quantity and quality; agriculture; health/disease; energy; and land use/migration. Presentations and discussions focused on three key questions. First, the availability of information on adaptation, in terms of the current state of the empirical literature for each climate impact area, remaining gaps, and the implications of current findings on adaptation for policy. Second, a critical look at the current state of IA modelling practice, the most important limitations to enhancing IAMs' ability to simulate impacts and adaption, and research needs to enable IAMs to better reflect empirical findings. Last, the contributions of improving the connection between empirical research and IA modelling with respect to what models should, and could, tackle in the near term, and the priorities for a longer-term research agenda.[11]

30. Turning now to the studies in Table 1, intertemporal optimization models are currently in the best overall position to assess the costs of climate impacts. They explicitly incorporate the intertemporal feedback effects of future climate damages on current energy use and abatement decisions, and represent Figure 1's web of influences from emissions to climate impacts to damages over a multi-century horizon. However, to render the assessment problem computationally tractable what ends up being sacrificed in the specification of damages is regional, sectoral and endpoint detail. All of the studies in this section using highly stylized regional (or global) value-added production functions in conjunction with aggregate climate damage functions forced by changes in global mean temperature. The fundamental basis for these studies remains Nordhaus and Boyer's (2000) study of the temperature dependence of seven specific impact endpoints,[12] which are then aggregated into regional damage functions. Attempts have been made to incorporate newer damage estimates from models such as FUND and empirical results summarized in Agrawala and Fankhauser (2008) and UNFCCC (2007), but the necessary values are missing for many sectors and endpoints, necessitating the use of judgment and assumptions to fill the relevant gaps. Furthermore, the resulting region-specific estimates of the costs of adaptation and residual damage are ultimately added up to yield functions of global climate change, making it impossible to discern the extent to which guesses, interpolation and aggregation drive their results. Finally, climate damages are generated

[11] The conference program is available online at http://conference.nber.org/confer/2012/IAMs12/program.html

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

by imposing impacts as neutral adverse productivity shocks which directly affect GDP, with no accounting for effects on factor inputs.

31. The advantage of computable general equilibrium (CGE) models is their ability to comprehensively represent regional and sectoral differences in climate impacts. But this typically comes at the cost of an inability to capture intertemporal feedbacks, which are limited by computational constraints to a few regions or sectors over a short time-horizon.[13] Thus, a common feature of the CGE models listed in Table 1 is that they are either static simulations of a current or future time period (e.g., Bosello et al. 2006; 2007a,b; Roson and Van der Mensbrugghe, 2012; Ciscar et al. 2011) or recursive dynamic simulations that step through time driven by endogenous accumulation of capital with investment determined by current economic variables (e.g., Deke, 2001; Eboli et al., 2010; Bosello et al., 2012), with comparatively short simulation horizons - typically the year 2050. Consequently, they lack the structure to simulate proactive investments, and are mostly restricted to analysing the welfare implications of Type I adaptations. It is also possible to introduce Type II adaptation via side-constraints on the general equilibrium problem, but this has not been done due to the lack of available data to calibrate the necessary investment functions. Type III adaptations can only be introduced as exogenously prescribed scenarios of investment. Exceptions are Bosello and Zhang (2006) and Bosello et al. (2010b), who couple CGE and optimal growth models as way of introducing intertemporal feedbacks into the former in order to specify the intertemporally optimal levels of proactive adaptation.

32. Except for Eboli et al. (2010), Bosello et al. (2012) and Ciscar et al. (2011), CGE studies tend to investigate the broad multi-market effects of one or two impact endpoints at a time. The magnitudes of these forcing variables and their influences on the sectors in the model are determined exogenously and imposed as shocks to sectoral productivity or to the endowments of resources such as land. The typical procedure is to run GCMs output at the regional scale through impact models to generate a vector of endpoint intensities in a particular impact category. The result is a region-by-sector array of shocks which form the inputs to counterfactual simulations of the CGE model. The model then calculates the ex-post web of intersectoral and interregional adjustments, as a way of estimating the consequences for sectoral output, and regions' aggregate net products.

33. The advantage of sector-based partial-equilibrium economic models is their ability to represent in a detailed fashion the activities and technology options that constitute production within a particular area of the economy. However, their limited scope prevents them from capturing multi-market general equilibrium effects. The fact that agriculture and forestry are the sectors best represented by this class of model suggests that this omission is more likely to bias estimates of the climate's economic consequences in poorer developing countries in which these activities make up a substantial fraction of GDP. Models' regional coverage also varies. Some (e.g., Rosegrant et al., 2008) are global in scope and resolving regional detail, while others (e.g., Adams et al., 1996) are limited to a single region—most often the US. In the time dimension, some models (Sohngen et al., 2001) are able to incorporate intertemporal feedbacks, while others are recursive dynamic (Rosegrant et al., 2008). But notwithstanding such diversity, these models as a class have yet to seriously exploit opportunities to represent process-level details of impact endpoints' effects on the sector being simulated. Here again, the difficulty is the need to rely on upstream models to translate climatic changes into usable impact endpoints at regional scales.

34. Lastly, models such as PAGE (Plambeck et al., 2007; Hope, 2006) and FUND do not optimize an economic objective, but instead simulate the interconnected feedback relationships that underlie the diagram in Figure 1. Both models divide the world into a number of regions, each of which has multiple damage functions that correspond to "impact sectors"—a hybrid of the impact endpoint and economic

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

sector categories. PAGE models only aggregate market and non-market damages, while FUND includes ten sectors.[14] Monetary damages are specified directly as functions of per capita income, which in both models is exogenous and scenario-driven, and global or regional temperature changes. The latter are calculated from accumulated GHG emissions generated by applying time-varying emission factors to GDP. The functional forms and numerical parameterizations of these damage relationships draw on a wide variety of sources, from summaries of empirical work to model results, but their key characteristic is that the precise linkages are far from transparent, especially with regard to regional variations in underlying endpoints. Adaptation is both explicit and implicit in these models. In PAGE adaptation is applied parametrically by the analyst as a policy variable. FUND simulates specific adaptation costs as a component of damages in the agricultural and coastal sectors, while treating adaptation implicitly in other sectors such as energy and human health through the reduction in regions' vulnerability to impacts with increasing wealth. An interesting feature of PAGE is its explicit treatment of uncertainty by incorporating stochastic catastrophic damages and explicitly specifying 31 key inputs to marginal impact calculations as probability distributions. The fact that FUND's fast runtime and minimal data input facilitates rapid generation of vectors of costs in different impact categories and regions accounts for its continued appeal.

3.2 A Review of Damage Cost Estimates

35. In light of these caveats, do the studies in Table 1 tell us anything useful about the magnitude of climate damages? A simple answer is elusive. Even within a particular impact category, damage estimates vary according to the scenario of warming or other climate forcing used to drive impact endpoints, the sectoral and regional resolution of the resulting shocks and the models used to simulate their economic effects, and the substitution possibilities within the latter and whether or not they include the costs and benefits deliberate investments in adaptation. Sorting through these details is tedious; tracing their influence on numerical damage estimates is virtually impossible due to the unavoidable omission of modelling details necessitated by journal articles' terse exposition. Indeed, a pervasive obstacle is insufficiently detailed documentation of the precise steps, judgment and assumptions involved in constructing region-by-sector arrays of economic shocks out of inevitably patchy empirical evidence.

36. Table 3 gives a sense of the relevant variation across six modelling studies that focus on the economic effects of various endpoints in the year 2050. All of the studies use input-based accounting to simulate the economic consequences using CGE models, and several features of their results are noteworthy. The magnitude of economic consequences is generally small, rarely exceeding one tenth of one percent of GDP. Effects also vary in sign, with some regions benefiting from increased output while others sustaining losses. There does not appear to be obvious systematic variation in the sign of effects, either across different endpoints or among regions, but finding such patterns is complicated by a host of confounding factors. The studies use different climate change scenarios, and for each impact category economic shocks are constructed from distinct sets of empirical and modelling studies, each with its own regional and sectoral coverage, using different procedures.

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

Table 3. Damage costs of climate impacts to the year 2050: selected CGE modelling studies

Forcing Scenario and Input Data	Impact Endpoints, Economic Shocks and Damage Costs
	Agriculture (Bosello and Zhang, 2006)
0.93°C global mean temperature rise; temperature-agricultural output relationship calculated by FUND	Endpoints considered: temperature, CO2 fertilization effects on agricultural productivity Shocks: land productivity in crop sectors Change in GDP from baseline: 0.006-0.07% increases in rest of Annex 1 regions, 0.01-0.025% loss in USA and energy exporting countries, -0.13% loss in the rest of the world
	Energy Demand (Bosello et al., 2007a)
0.93°C global mean temperature rise; temperature-energy demand elasticities from De Cian et al. (2013)	Endpoints considered: temperature effects on demand for 4 energy commodities Shocks: productivity of intermediate and final energy uses Change in GDP from baseline: 0.04-0.29% loss in rest of Annex 1 regions, 0.004-0.03% increase in Japan, China/India and the rest of the world, 0.3% loss in energy exporting countries. Results for the case of perfect competition only
	Health (Bosello et al., 2006)
1°C global mean temperature rise; temperature-disease and disease-cost relationships extrapolated from numerous empirical and modelling studies	Endpoints considered: malaria, schistosomiasis, dengue fever, cardiovascular disease, respiratory ailments, diarrheal disease Shocks: labour productivity, increased household expenditures on public and private health care, reduced expenditures on other commodities Direct costs/benefits (% of GDP): 9% in US and Europe, 11% in Japan and the remainder of the Annex 1, 14% in Eastern Europe and Russia, benefits of 1% in energy exporters and 3% in the rest of the world Change in GDP from baseline: 0.04-0.08% increase in Annex 1 regions, 0.07-0.1% loss in energy exporting countries and the rest of the world
	Sea level rise/Tourism (Bigano et al., 2008)
Uniform global 25cm sea level rise; land loss calculated by FUND	Endpoints considered: land loss, change in tourism arrivals as a function of land loss Shocks: reduction in land endowment Direct costs (% of GDP): < 0.005% loss in most regions, 0.05% in North Africa, 0.1-0.16% South- and South-East Asia and 0.24% in Sub-Saharan Africa. Costs are due to land loss only. Change in GDP from baseline: < 0.0075% loss in most regions, 0.06 in South Asia and 0.1% in South-East Asia
	Ecosystem services (Bosello et al., 2011)
1.2°C/3.1°C temperature rise, with and without impacts on ecosystems	Endpoints considered: timber and agricultural production, forest/cropland/ grassland carbon sequestration Shocks: reduced land productivity, reduced carbon sequestration resulting in increased temperature change impacts on 5 endpoints in Eboli et al. (2010) Change in GDP (3.1°C, 2001-2050 NPV @ 3%): $22-$32Bn additional loss in E. and Mediterranean Europe, $5Bn reduction in loss in N. Europe
	Water Resources (Calzadilla et al., 2010)
Scenarios of rainfed and irrigated crop production, irrigation efficiency based on Rosegrant et al. (2002)	Endpoints considered: crop production Shocks: supply/productivity of irrigation services Change in Welfare: losses in 5 regions range from $60M in Sub-Saharan Africa to $442M in Australia/New Zealand, gains in 11 regions range from 180M in the rest of the world to $3Bn in Japan/Korea

Source: authors' elaboration of Bosello and Zhang (2006), Bosello et al. (2006, 2007a, 2011), Bigano et al. (2008) and Calzadilla et al. (2010).

37. Consistent with Figure 2, shocks tend to be computed as percentage changes in the value of output or inputs. Two of the papers impose these changes on projected baseline economic variables, and express the resulting estimates of ex-ante direct damage as a share of GDP. These numbers are uniformly negative for land loss due to sea level rise, and negative for health with the puzzling exception of energy exporting countries and other developing areas. In turn, when these shocks are propagated through CGE models' systems of interacting markets, even regions experiencing adverse effects can end up benefiting. Although such results are surely influenced by both substitution and adjustments in investment and international trade, the key issue is how these forces combine to determine the final outcome—which is ripe for investigation given analytical advances over the past decade (e.g., Harrison et al., 2000;

Boehringer and Rutherford, 2004). Another caveat is that while GDP is ubiquitously used as a measure of macroeconomic cost, it suffers from serious theoretical and practical limitations. When used to quantify the impact of a shock on an initially tariff-ridden economy, the sign of GDP changes can be counterintuitive ways in the presence of small shocks. However, quite apart from the “black box” critique of CGE modelling (for more explanation see Sue Wing, 2009, 2011), the more fundamental open questions for the purposes of this review are the signs and magnitudes of the shocks themselves, and the details of the methods used to incorporate them into models—information which tends to be reported only in a summary fashion.

38. Fortunately, new changes in climate into changes in impact endpoints and shocks to economic sectors r analyses by Ciscar et al. (2009, 2011, 2012) and Bosello et al. (2012a,b) begin to make significant headway in addressing these issues. Tables 6 and 7 in Annex II summarize the main inputs to, and outputs of, the PESETA study of climate impacts on Europe in 2050. Estimates of physical impacts were constructed by propagating a consistent set of climate warming scenarios through different process simulations in four impact categories: agriculture (Iglesias et al., 2012), flooding (Feyen et al., 2012), sea-level rise (Bosello et al., 2012c), and tourism (Amelung and Moreno, 2012).[15] The results were then incorporated into the GEM-E3 CGE model using a variety of techniques to map the endpoints generated by process simulations onto the types of effects on economic sectors catalogued in Figure 2 (Ciscar et al., 2012). Changes in crop yields from the agricultural assessment were implemented as total factor productivity (TFP) declines in the agriculture sector. The river flood assessment’s expected damages by water depth and the land-use class were implemented as additional expenditure that must be undertaken by households, secular reductions in the output of the agriculture sector, and reductions in the outputs of and capital inputs to industrial and commercial sectors. Changes in occupancy from the tourism assessment are combined with statistics on “per bed-night” expenditures to estimate changes in tourist spending by country, which are then expressed as secular changes in exports of GEM-E3’s market services sector. The sea-level rise assessment computes land losses, consequent migration, as well as damage from coastal flooding. As with river flooding, costs associated with migration are assumed to fall on households as additional expenditure, while coastal flooding is assumed to equiproportionally reduce sectors’ endowments of capital. The direct effect of land loss on the macroeconomy was not considered because GEM-E3 does not explicitly resolve land as a factor of production.

39. Despite being exceptionally well documented and transparent, the major shortcoming of this analysis is its narrow geographic scope. That issue is addressed by Bosello et al. (2012a,b), the inputs to which and outputs of which are summarized in Tables 8 and 9 in Annex III. Estimates of physical impacts were derived from the results of different process simulations forced by the SRES A1B climate change scenario (1.9°C global mean temperature increase) in six impact categories for the year 2050: agriculture (changes in average crop productivity simulated by the ClimateCrop model - Iglesias et al., 2011), tourism (changes in arrivals simulated using the Hamburg Tourism Model - Bigano et al., 2007), residential energy demand (changes simulated by the POLES energy system model - Mima et al., 2011), forestry (changes in net primary productivity (NPP) simulated the LPJmL dynamic global vegetation model - Bondeau et al., 2007; Tietjen et al., 2009), river flooding (costs based on results of the LISFLOOD simulation, for Europe only - Van der Knijff et al., 2010), and aggregate labour productivity (changes in worker performance with heat and humidity - Kjellstrom et al., 2009). However, in a number of impact categories (e.g., health) documentation of key details of the endpoint calculations could be strengthened.

40. These endpoints were then expressed as shocks within the ICES CGE model. Regional impacts on energy and tourism were treated as shocks to household demand. Changes in final demand for oil, gas, and electricity were expressed as biased productivity shifts in the aggregate unit expenditure function. A two-track strategy was adopted to simulate changes in tourism flows, with non-price climate-driven

[15] Health impacts are also assessed (Watkiss and Hunt, 2012), but their economic effects are not quantified.

substitution effects captured through secular productivity biases which scale regional households' demands for market services (the ICES commodity which includes recreation), and the corresponding income effects imposed as direct changes in regional expenditure. Regional impacts on agriculture and forestry, health, and the effects of river floods and sea-level rise, were treated as supply-side shocks. Changes in agricultural yields and forest NPP were represented as exogenous changes in the productivity of the land endowment in the agriculture sector and the natural resource endowment in the timber sector, respectively. Reduction in aggregate labour productivity was used to model the employment performance impacts of higher temperatures. Losses of land and buildings due to sea-level rise were expressed as secular reductions in regional endowments of land and capital, which are assumed to decline by the same fraction. Damages from river flooding span multiple sectors and are therefore imposed using different methods: reduction of the endowment of arable land in agriculture and equiproportional reduction in the productivity of capital inputs to other industry sectors, as well as reductions in labour productivity (equivalent to a one-week average annual loss of working days per year in each region) for affected populations. Here too, the transparency of the procedures used to translate the aforementioned endpoints into the shocks in Table 6 leaves much to be desired.

4. Ways Forward: Sector-Based Approaches to Modelling Impacts at Regional Scales

41. Given the limitations of the studies reviewed in Section 3.2, the critical question is what improvements can be made to existing methods and data to better capture the global economic implications of climate impacts at regional scales. In particular, it is useful to identify the options for estimating impact endpoints given existing data, as well as the instances where progress relies on fundamental data gathering. Similarly, it is useful to survey the options for translating endpoints into shocks to be incorporated within IAMs, especially multi-region, multi-sector CGE models of the type used by Ciscar et al. (2009, 2011, 2012) and Bosello et al. (2012a,b). Lastly, it is important to ask how to enhance understanding of the regional incidence of the impacts already considered by these studies, and expand the scope of analysis to new impact categories.

42. This section attempts to address these questions by offering an in-depth discussion of key implementation issues that must be tackled in model-based assessments of the costs of climate impacts. Following the canonical model advanced in Section 2.3, the first order of business is to identify and classify the key economically relevant impacts of climate change. The focus is on the 11 "impact sectors" considered by the US National Climate Assessment (NCADAC, 2013): agriculture, fisheries, energy supply, energy use, water resources, human health, transportation, forestry, land use and land cover change, sea level rise, extreme events, and ecosystems and biodiversity.[16] The second challenge is to identify both the specific biophysical impact endpoints associated with these categories, and the sectors and activities within the economy which each endpoint affects. Methodological alternatives for constructing shocks associated with each endpoint/sector combination, and incorporating them within IAMs, are then outlined in detail. For the most part the discussion strives to be generic. In particular, it

[16] These categories provide an elaboration of IPCC's sectoral groupings (IPCC, 2007; Field et al., 2012 - Freshwater resources and their management, Ecosystems, Food, fibre and forest products, Coastal systems and low-lying areas, Industry, settlement and society, Health), encompassing the same basic set of impacts while organizing them in a manner that is easier to articulate with the representation of the economy within IAMs. This study does not explicitly consider "systemic" risks from rapid nonlinear shifts in the climate system state (e.g., hypothetical sudden change in the Asian monsoon or disintegration of the West Antarctic ice sheet) that potentially give rise to cascading adverse impacts that are large in magnitude, span multiple endpoints, and manifest themselves over broad geographic scales (IPCC, 2007; Field et al., 2012). Notwithstanding the justifiable concern that such risks may be critical drivers of climate damages that IAMs fail to capture (Stern, 2013), the lack of physical understanding of—and data on—both the underlying nonlinearities themselves and the complementarities among endpoints which they might induce, prove to be insurmountable impediments to analysis.

sidesteps the thorny issues of timing and geographic distribution of both changes in climate variables and the impact endpoints to which they give rise. Nevertheless, the discussion is less general in one key respect: the details of the approaches tend to be targeted at CGE models, because of their versatility in resolving regional and sectoral differences in impacts' effects, articulating the economy's web of supply-demand linkages, and providing a detailed representation of firms' and households' substitution possibilities. Even so, the breadth of scope of impact categories, both regionally and in terms of the range and diversity of human and natural systems that they could potential affect, make it very likely that some impact pathways will be missed.

43. Table 4 in Annex I provides an overview of this section's findings. Strategies for representing climate impacts fall into two basic categories: shocks to the productivity of one or more economic sectors, and shocks to the supply of one or more factors of production that are specific to the sector under consideration. The former category is more broadly applicable to the categories of impacts under consideration, and can be further divided into neutral shocks that affect the productivity of all inputs, or biased shocks that affect the productivity of only some inputs (typically one). In the latter category, implementation turns on the trick of appropriately defining the climate-related non-reproducible factor.

4.1 Agriculture

44. Agriculture is one of the best-studied sectors in terms of the exposure to, and effects of, climate change impacts. Changes in the level and timing of temperature and precipitation over the growing season have a direct and predictable influence on the growth and ultimate productivity of particular crops growing in a particular type of soil, and agroecosystem or crop production models (e.g., DSSAT, DNDC, EPIC) have long been able to simulate the resulting effect on yields (crop production per harvested area) under different management regimes. Nonetheless, these models were originally designed as decision support tools for agricultural extension, to answer the question of what yields could be expected in a particular location, given observations of its soils and past weather. Akin to the first generation of global climate models in the IPCC First Assessment Report (IPCC, 1990), only comparatively recently have they been pressed into service to assess the impacts of changes in meteorological variables on yields. As with all impacts models, the assessment procedure simulates the yields of various crops in a number of locations across the globe (e.g., representative grid cells) using temperature and precipitation for an average growing season under current climate, and again using projections of meteorology for a future year under scenarios of climate warming. The resulting climate shocks to yields can then be used as an input to techno-economic agriculture sector or macroeconomic models. These models were not designed to capture the yield impacts of climate extremes, and their capabilities for doing vary in ways that are not well understood. Indeed, addressing this knowledge gap is a key motivation for the ongoing Agricultural Modelling Intercomparison Project (AgMIP).[17]

45. Given this state of affairs, attention has shifted to statistical approaches to estimating macro-scale relationships between crop yields and temperature and precipitation. Regression-based methods have long been used, in the past focusing on fitting polynomial response surfaces of yield responses to temperature and precipitation. Recent approaches have employed flexible semi-parametric techniques that employ weather shocks to statistically identify yield response functions at various geographic scales—from US counties (Schlenker and Roberts, 2009) to countries (Lobell et al., 2011). Flexibility is the main advantage of this methodology: it alleviates the need to run a complex model every time a new scenario of climate warming needs to be assessed. However, there remains the issue of how to translate these changes in yields generated by coupling these response functions with GCM output.

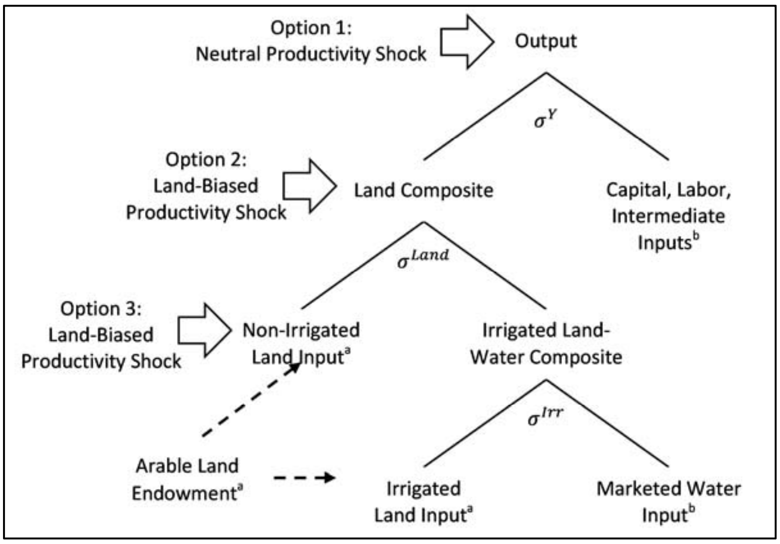
[17] http://agmip.org

46. Assessments of agricultural impacts that use global economic models with highly aggregated geographic units (e.g., Europe as a single region) typically require a procedure to bridge geographic scales. For example, Lobell et al.'s (2011) unit of analysis is the country, which is the level at which their statistical climate response surface predicts yields. Shocks to crop productivity at the level of the model's regions will therefore need to be constructed by spatially aggregating the yield changes derived from their econometric estimates and GCM output. A variety of aggregation procedures can be used; the key insight is that the resulting regional shocks represent the climate impact on the productivity of a particular crop sector, controlling for other influences. If harvested areas remain invariant to climate change, yield changes are indicative of changes in production, suggesting that the aggregate productivity impact of finer-scale yield shocks can be consistently estimated by their area-weighted average. Since the acreage of individual crops can also change, it is preferable to differentiate at least major crops within the model so that the adaptation and crop substitution is endogenous in the model. If this is not possible, assumptions need to be made in order to compute the aggregate productivity impact. One potentially attractive option is Diffenbaugh et al.'s (2012) use of benchmark production shares under the current climate to derive economy-wide climate shocks to US maize productivity.

47. An additional issue is the precise way in which climate shocks affect crop sectors. The essential characteristic of climate impacts is that they alter the productivity of land in a particular locale. However, the extent to which studies are able to isolate this effect depends on the factors they are able to control for in the process of constructing climate shocks - management practices in crop-climate simulations and variations in inputs (irrigation, agrochemicals, mechanization) and technology (e.g., high-yielding varieties) in econometric studies. Arguably, the components of these factors that exhibit statistical covariation with low-frequency shifts in temperature and precipitation represents historical adaptation to climate change. Inability to isolate estimated climate-yield relationships from the influence of these components suggests that the resulting yield response functions will capture the effect of climate on the productivity of all inputs, as opposed to land alone. This raises an important translational question: how should climate shocks constructed from these responses be incorporated within economic models? The foregoing discussion argues that shocks derived from crop modelling or empirical studies that are uncontrolled should be implemented as neutral productivity shifts in crop production or cost functions (which is the strategy employed by Diffenbaugh et al., 2012), while shocks derived from analyses that are able to control for historical adaptation should be implemented as biased productivity factors applied to crop sectors' inputs of land.

48. Prerequisite to latter approach is the specification of land as an input to crop production by the economic model under consideration. Recent CGE modelling approaches employ a nested production function that treats land as a quasi-fixed factor that is a component value-added composite along with labour and capital (Calzadilla et al., 2010). In agriculture sectors, promoting land to the top level of the production hierarchy allows the analyst more flexibility in the choice between using neutral and land-biased productivity parameters to specify climate shocks. The key elements are the top-level elasticity of substitution between land and other inputs (which determines the potential for producers to substitute reproducible inputs for land as its quality is diminished by the climate shock), as well as the inclusion in the production function of discrete technology options that can mitigate the shock, such as irrigation. This is shown schematically in Figure 3, which illustrates three options for modelling climate shocks to yields.

Figure 3. Climate impacts on agricultural yields: hierarchical crop sector production function



a Different crop sectors compete for the economy's aggregate supply of arable land.

b In a model with differentiated land, marketed water is separate from other intermediate inputs.

Source: authors drawing on the GCE modelling literature.

49. In the neutral productivity case (option 1) it is even possible to subsume the details of substitution between land and other inputs to production, whereas in the biased productivity cases, shocks affect the productivity of land. Option 2 allows land to be modelled as a homogeneous factor, in which case the impact on sectoral production is determined by land's cost share and the elasticity of substitution, σ^{Y}. Option 3 requires land to be differentiated into irrigated and non-irrigated components, with the latter being affected by the shock, and the former specified as a composite of irrigated land and purchases of marketed water. The impact on production is determined by the ability to substitute irrigated for non-irrigated acreage (governed by the elasticity σ^{Land}), which in turn depends on the elasticity of irrigated land supply that is a function of the intensity of water application (determined by the elasticity σ^{Irr}).

50. The principal feature of this formulation is that neither land nor marketed water are fixed factors; on the contrary each crop sector must compete with others for inputs of land and irrigation. For this reason agriculture sectors' initial demands for land and water need to be calibrated; a procedure which is likely to be most straightforward in global economic models that rely on the GTAP database's satellite land use accounts (Hertel, 2008). Nevertheless, calibrating the crop-wise division of arable land between irrigated and non-irrigated production is likely to remain a key challenge, and will probably necessitate reliance on ancillary data sources on irrigation extent, such as the MIRCA database (Portmann et al., 2010).

4.2 Fisheries

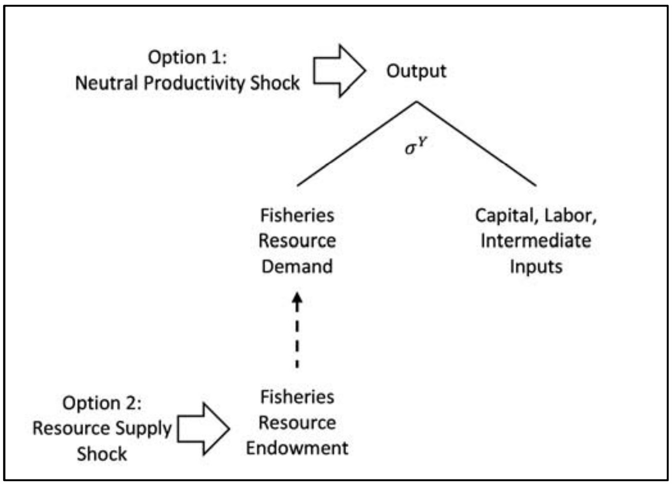
51. In comparison to agriculture, the effects of climate change on fisheries have not been characterized in as much detail, and, despite the rapid pace of accumulation of knowledge about the relevant biophysical mechanisms, the implications of their combined responses at the ecosystem level remain poorly understood.[18] Ocean acidification due to dissolved CO_2, as well as shifts in the patterns of meteorological variables are likely to affect the physiology and behaviour of marine organisms, with a

[18] This discussion excludes impacts on aquaculture.

variety of impacts on the populations of different species (e.g., changes in spatial range, population size and rates of growth, seasonal abundance) and ecosystem-level interactions (e.g., competition, grazing, predation, and disease dynamics) (Doney et al., 2012). The precise manner in which consequent changes in community structure and diversity will affect the ecosystem services upon which the fisheries rely is not known, however the implications for harvesting effort and yields are likely to be heterogeneous, and species- and location-specific.

52. Adverse impacts of climate change on fisheries reduce the return to harvesting effort, lowering the returns to inputs of primary factors and intermediate inputs to the sector. As illustrated in Figure 4, this effect may be modelled simply as a neutral productivity shock to the sector's production function (option 1). An alternative, more nuanced approach treats labour, capital and intermediate goods as relative complements to a biophysical marine resource whose supply and/or productivity is a function of climatic conditions. In a CGE modelling framework, such a resource can be thought of as a sector-specific fixed factor with which households are endowed. The resource differs from arable land in Section 3.1, in terms of not only the latter's mobility among crop sectors, but also because agricultural impacts are associated with changes in the quality but not the aggregate quantity of land. In fisheries the quantity as well as the quality of the underlying resource is potentially affected, both of which can be modelled through a secular reduction in the economy's marine ecosystem fixed factor endowment (option 2).

Figure 4. Modelling climate impacts on fisheries: Fisheries sector production function



Source: authors drawing on the GCE modelling literature.

53. The latter approach requires calibration of the fixed factor, which is challenging because the value of the resource is not recorded in standard economic accounts, and so must be assumed by the analyst. A typical strategy for circumventing this problem is to treat some fraction of the returns to capital as indicative of payments to the resource, with the relevant share being a matter of judgment. The payoff is that this creates an opening to employ are well-established techniques to calibrate the value of the elasticity of substitution between reproducible inputs and the resource (σ^Y) to be consistent with empirically-determined supply elasticities (e.g., Rutherford, 1998). The more difficult issue is how to specify the change in different regions' fixed-factor endowments in response to the climatic changes they experience, which, given the current state of knowledge, is likely to be little more than guesswork. In this regard, a useful place to start might be studies of regional changes in species distribution and abundance due to climate forcing over broad geographic scales (e.g., Cheung et al., 2009, 2012). Their findings on the changes in biomass of fish generally, and economically important species in particular, might be used in conjunction with landing statistics (e.g., from the Food & Agriculture Organization's Fisheries and

Aquaculture Information and Statistics Service) to construct the necessary region-specific shocks to fisheries' resource endowments.

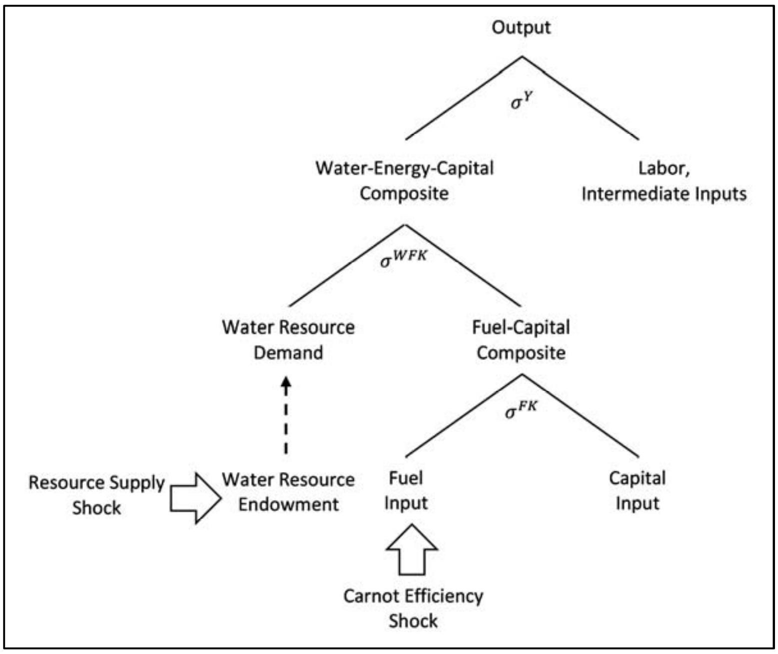
4.3 Energy Supply

54. There has been substantial recent interest in the "climate-energy-water nexus", which refers to the potential adverse effects of climate change impacts on supplies of surface water necessary for hydroelectric generation and thermoelectric cooling, and of consequent energy supply constraints on the ability to move fresh water for agricultural, industrial and urban uses. In this subsection I focus on the forward implication water impacts on energy supply, which is the subject of intensive research in the US (DOE, 2006, 2008, 2009; Markoff and Cullen, 2008) and Europe (Golombek et al., 2012; Linnerud et al., 2011; Mideksa and Kallbekken, 2010) but less well characterized elsewhere (Siddiqi and Anadon, 2011). Aside from the risks to energy transformation and distribution infrastructure posed by sea-level rise and severe storms, current attention on the impacts of climate change on energy supply tend to focus on the electric power sector. For this reason, integrated assessments of the associated impact pathways must rely on IAMs that are capable of resolving water as an input to electric power production and distinguishing between discrete "bottom-up" technology options in the sector.

55. The essence of the approach is to subject key water-using electricity generators (e.g., hydro or thermoelectric coal-fired or nuclear generation) to differentiated productivity shocks which are a function of the projected impact of precipitation and evapotranspiration changes on surface runoff and discharge, and projected stream withdrawal rates per kWh. This function can be thought of as a reduced-form response surface in which the first variable captures the water supply response to climate impacts, and the second indicates the intensity of demand. (For thermoelectric power, unit demands may shift due to the Type III reactive or proactive adaptation measures to retrofit existing once-through to create more efficient dry cooling systems, a change that can either be imposed by the analyst as adaptation scenarios or modelled as an endogenous process, though the second option is likely to be challenging to implement and beset by a dearth of empirical evidence.) It seems logical that constraints on stream withdrawals impact the productivity of hydro generation in a neutral fashion and cannot be mitigated by substitution of reproducible inputs. By contrast, the productivity shock to thermoelectric generation operates through these technologies' use of non-marketed water, which can be modelled as a fixed-factor resource input whose supply is curtailed by climate change.

56. Lastly, warmer ambient temperatures directly impact thermal generation units' Carnot cycle efficiencies, with a modest adverse effect that is biased toward using fuel. This can be implemented as an energy input-biased productivity shock whose magnitude is determined by empirical-estimated generation-temperature relationships—once they adequately control for spurious demand-side effects (cf Linnerud et al., 2011). The procedure for incorporating the joint impacts of shocks to thermal efficiency and cooling water availability into the hierarchical production function of an electric generator is shown schematically in Figure 5.

Figure 5. Modelling climate impacts on electricity supply: a generator's production function



Source: authors drawing on the GCE modelling literature.

4.4 Energy Use

57. There is a vast empirical literature on energy demand functions. One of the main characteristics of these studies is that in such studies, temperature (and to a lesser extent, humidity) has long been included as statistical controls to increase the precision of estimated price and income elasticities (cf Maddala et al., 1997; Alberini and Filippini, 2011). Concern over the climate change impacts on energy systems has focused attention on the effects of meteorological variables in their own right, and has led to the development of more precise estimates of the effects of temperature shocks. This, coupled with the widespread availability of engineering and econometric estimates of the response to temperature of sectors' and households' demands for fuels and electricity, enables energy demand impacts to be modelled in a straightforward fashion. Shocks to demand can be calculated as the product of the relevant sector-specific temperature elasticities and the percentage change in temperature relative to current climate experienced under scenarios of global warming. The resulting factors can then be incorporated in IAMs as exogenous shift parameters in energy demand functions and biased productivity factors in cost and expenditure functions (e.g., De Cian et al. 2013; Sue Wing, 2013).

58. However, notwithstanding the ease of implementation, issues of aggregation still need to be considered. Unless the demand response estimates and resulting shocks are calculated at the same temporal and spatial scale as the simulation into which they will be incorporated, aggregation along both dimensions will be necessary. For example, De Cian et al.'s (2013) estimates of the responses to temperature of annual demand for various energy commodities in a sample of countries are stratified by region, which enables them to be used by Roson et al. (2007) in a CGE model that divides the world economy into several regions. Even so, imperfect regional overlap between estimation and simulation means that several regions are constrained to have similar temperature responses—though not ultimate shocks, which depend on temperature differences which vary geographically. Sue Wing's (2013) estimates of US states' monthly electricity demand response show small reductions in demand in autumn, winter and spring that are offset by substantial increases in peak summer demand. The inner product of these results and states' prevailing

monthly load patterns yields projected increases in annual electricity use whose magnitudes exhibit a strong geographic gradient. Sue Wing uses these results directly in a state-level inter-regional CGE model of the US economy, but their use to derive shocks to a single-region model would necessitate aggregation using subnational administrative units' shares of national demand.

59. A final, important caveat concerns what Mansur and Auffhammer (2012) refer to as the "extensive margin", namely, adjustment of quasi-fixed energy-using capital stocks over the long run as opposed to the short-run adjustments in variable energy inputs to production and consumption. Adjustments along the extensive margin in the form of residential air conditioner purchases are an adaptation response to increased cooling demands as a result of climate change (Barreca et al., 2013), and one which can dramatically increase long-term energy use. The endogenous effect of climate variables—or their impacts on human systems—on the diffusion of energy using capital has not been systematically examined outside the US (Sailor and Pavlova, 2003; Mansur et al., 2008), most likely due to lack of suitable data. This issue is ripe for investigation, particularly in very populous industrializing developing countries such as China and India where the market penetration of space conditioning is currently low and expected to increase rapidly with rising affluence.

4.5 Water Resources

60. Climate change potentially affects three broad classes of water resources: net precipitation—precipitation in excess of evapotranspiration, which directly impacts the supply of soil moisture and productivity of rain-fed agriculture; renewable surface water—runoff that feeds rivers, lakes, reservoirs, and shallow ground water aquifers subject to recharge; and, indirectly, non-renewable "fossil" groundwater—mining of which becomes more attractive with increased scarcity of the first two categories. While all three types of resources have economic value, only the subset of the second which is captured, stored and distributed to end-users (so-called "marketed water") is actually subject to a market-determined price.

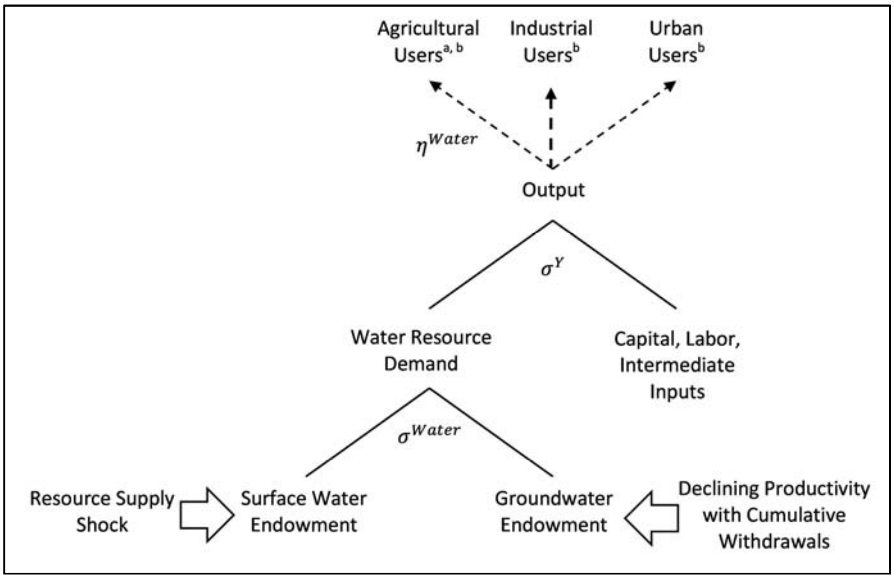
61. The focus of concern over the water resource impacts of climate change is the threat of correlated adverse shocks to precipitation and runoff. In Figure 2, declines in precipitation induce agricultural producers to substitute toward irrigation water inputs, which can be thought of as marketed water, whose demand increases. But drought conditions will simultaneously cause declines runoff and available water from streams and reservoirs, reducing the aggregate supply of marketed water that can be allocated between agricultural and other uses, and exacerbating scarcity. Incorporating this impact pathway within IAMs requires at least some capability to represent the water balance. Figure 6 illustrates perhaps the simplest option, which is to model natural water as a fixed-factor resource input to a water distribution sector.[19]

62. The remaining inputs of capital, labour and energy to the sector then represent costs of collection, storage and conveyance to end users of withdrawals from the resource, with the implication that the elasticity of substitution $\sigma^{Y} \rightarrow 0$. The resource itself is divided between runoff that is subject to climate shocks, and groundwater which is finite and depletable. Reductions in runoff induce water producers to substitute toward groundwater mining (with ease governed by the substitution elasticity σ^{Water}), implying that adaptation becomes increasingly costly over time as the groundwater resource is depleted and the costs of locating and lifting fossil water rise. The latter effect can be modelled using a long-run supply function in which cumulative groundwater withdrawals reduce the productivity of the groundwater resource, resulting in a downward scaling of the relevant endowment. This approach contrasts with Calzadilla et al.'s (2010, 2011) representation of irrigation water as a primary factor input to crop sectors in the GTAP-W model. Such a lack of detail on the supply side is symptomatic of the paucity of information on the impacts

[19] For example, the WTR sector in the GTAP database can be used as a proxy for broader distribution activities.

of climate change on the water balance at regional scales, a stumbling block which can be best addressed by coupling IAM simulations with large-scale hydrological models (e.g., WBMPlus, Wisser et al., 2010).

Figure 6. Modelling climate impacts on water resource: marketed water sector production function



a Inputs of marketed water in Figure 2.

b Water markets do not clear on price: differences among users' opportunity costs modelled using a CET function.

Source: authors drawing on the GCE modelling literature.

63. A final point concerns the importance of the institutional setting on the demand side. Worldwide, water is rarely traded in well-functioning markets. Block pricing, a plethora of heterogeneous technical restrictions on household usage patterns, or outright service interruptions—which often vary from one municipality to the next within the same region, and unregulated surface- and groundwater withdrawals by farmers, all lead to persistent water price differentials among agricultural, industrial and urban users which are unlikely to be equalized. Olmstead (2012) argues that the misallocation of marketed water as a consequence of these institutional characteristics can potentially lead to mal-adaptation to climate shocks. As illustrated in Figure 6, water price differentials can be captured by modelling the allocation of the output of the marketed water sector according to a constant elasticity of transformation (CET) formulation, in which the transformation elasticity (η^{Water}) determines the extent to which intersectoral differences in opportunity costs drive water reallocation. Adaptation through institutional responses that improve allocation can then be simulated parametrically as $\eta^{\text{Water}} \rightarrow \infty$.

4.6 Human Health

64. Climate change affects human health via the direct effects of variables such as temperature and humidity on physiology, the through the indirect channels of infectious disease prevalence and virulence on morbidity and mortality. A promising approach to assess these effects is to adapt the methodology developed by Matus et al. (2008) and Nam et al. (2010) for investigating the health effects of pollution in a general equilibrium setting. These authors specify air quality shocks to health service requirements (i.e., the cost of medical care) and lost labour and leisure in a CGE model, where the shocks are constructed using historical pollution levels, demographic information, and, most importantly, exposure-response (E-R) relationships. An important feature of these analyses is the differential impact of acute and chronic illness on different age groups: chronic conditions tend to be more prevalent among the older age cohorts

who have had more time for diseases to develop, which reduces the average years of life lost among the aggregate population. To capture the effects of this phenomenon, acute illnesses are modelled as reducing all cohorts' length of life by a fixed amount, while chronic illnesses are associated with death rates that are age-specific. Next, to translate these endpoints into aggregate labour and leisure losses, the authors construct a demographic model that tracks age cohorts, their exposure to adverse environmental conditions throughout their lifetime, and the corresponding cohort- and chronic disease-specific death rates, which are assumed to increase proportionally with chronic exposure.

65. The key piece of information that makes this approach feasible is the availability of a comprehensive battery of E-R relationships for a range of illnesses and pollutants (e.g., the ExternE project, Bickel and Friedrich, 2005). Unfortunately, there is a dearth of similar estimates regarding the dependence of disease-specific morbidity and mortality on climate variables, a situation which empirical studies have only recently begun to address (Barreca, 2010, 2012; Barreca and Shimshack, 2012; Barreca et al., 2013; Deschenes and Greenstone, 2011). Also, regarding occupational health outcomes, there is emerging evidence that exposure of individuals to high temperatures results in reductions of work effort generally (Kjellstrom et al., 2009; Kjellstrom and Crowe, 2011), as well as declines in hours worked in highly climate-exposed industries in particular (Graff Zivin and Neidell, 2013).[20] Modelling infectious diseases requires the additional step of characterizing transmission and exposure as functions of climate variables, which can then be used in conjunction with E-R relationships. Ideally, these relationships would be econometrically estimated using longitudinal data, but the paucity of observations in cross-country databases such as the Global Burden of Disease study, in conjunction with the inability to control for individuals' climatic exposure and other confounding risk-factors over their life cycle has so far proved intractably challenging. The final step is to develop and test methods for translating empirical results into changes in labour productivity and healthcare consumption. This will facilitate the specification of shocks as attenuation factors that reduce the baseline rates of growth of aggregate labour productivity, and as healthcare-biased productivity factors in households' expenditure functions.

4.7 Transportation

66. NCADAC (2013) discusses anticipated transport sector consequences of climate impact endpoints almost entirely in terms of risks to infrastructure from extreme events. Although prior CGE modelling studies have represented transport infrastructure in a highly aggregated fashion (Conrad, 1997; Conrad and Heng, 1997), the extent of exposure of this capital to such climate risk depends critically on its fine-scale geographic distribution, which is something that neither IAMs nor even large-scale transport-sector simulations have the capability to resolve. Promising approaches are to further geographically disaggregate, and incorporate representations of infrastructure capital into, existing transport-focused CGE models (e.g., Abrell, 2011), or aggregate up sub-national economic impact models which incorporate representations of the flows of goods and people across transport network links that are subject to disruption (e.g., Sue Wing et al. 2008; Park et al., 2011). Given the nascent state of this literature vis-a-vis the present focus on integrated assessment, it is most expeditious to subsume impacts on transportation under the broader treatment of extreme events (Section 4.10).

4.8 Forestry, Land Use and Land Cover Change

67. The fertilization effect of elevated atmospheric CO2 concentrations has a direct positive impact on the growth of natural and managed forests. Increases in the return frequency of forest fires at regional scales will tend to reduce net primary productivity (NPP) and timber yields below the future levels that

[20] i.e., primarily outdoor activities such as agriculture, forestry, fishing, hunting, construction and mining; transportation and utilities; manufacturing sectors where facilities are typically not climate controlled and the production process generates considerable heat.

would prevail in the absence of climate shocks. The NPP impacts of geographic shifts in agroecological zones can be positive or negative. All of these influences are simulated within forest ecosystem process simulations (for a review, see, e.g., Aaheim et al., 2011), but the research need is developing methods for translating the outputs of these models into changes in forestry sector yields. The fact that ecosystem simulations use CGM runs as inputs ties the time-path of climate's influence on timber growth to particular scenarios of global warming, which limits the range of shocks to forest productivity that downstream economic analyses are able to assess. Further, process models typically include simple parameterizations of management regimes, which exert additional important influences on timber growth that have the potential to attenuate the magnitude of adverse climate shocks to forest productivity. But these same management practices are also implicitly subsumed within economic models' forestry sector production or cost functions, with raises the issue of potential double counting of Type I passive adaptations.

68. The resulting shocks affect the productivity of reproducible inputs to forestry sector in ways different from those seen in agriculture. First, the occurrence of fires at higher-than-baseline frequencies has punctuated non-market impacts outside the forestry sector—principally damage to ecosystems, and destruction of building and infrastructure capital stocks and associated business interruption. These are best modelled in the same manner as other extreme events (see Section 4.10). Second, compared to field crops, forests are subject to long lags between planting and harvesting that typically exceed time-steps on which IAMs solve. Thus, while in reality climate shocks affect the productivity of land, it is not clear whether over simulated sub-rotation periods substitution of reproducible inputs for land can have substantial mitigating effects on productivity losses. Given these considerations it seems appropriate to model climate impacts as neutral productivity shocks to the forestry sector.

69. Broader linkages to land-use change manifest themselves through the competition for land among natural ecosystems, urban and industrial uses, managed forests and agriculture. Continuation of long-run trends of land conversion to urban and industrial uses is an overarching stressor whose impact is likely to exceed that of climate change (Haim et al., 2011; Reilly et al., 2012). However, the lack of comprehensive global land accounts outside of the agriculture and forestry sectors complicates IAMs' ability to capture this important phenomenon. For example, the Global Trade Analysis Project (GTAP) land use database disaggregates the returns to land in forestry, livestock and several crop sectors in 113 world regions among 18 AEZs (Hertel et al., 2009), but does not record either the quantity or value of land in urban and industrial uses. It is possible to impute the total urban area and natural ecosystem extent using remotely sensed data (Friedl et al., 2010; Schneider et al., 2010). However, to endogenously simulate the change in allocation of land to agriculture and forestry in each AEZ requires, first, translational research to integrate these data into the economic accounts on which IAMs are calibrated, and second, the specification of behavioural models of land transitions. With regard to the former, the major challenge is imputing economic returns to land under natural ecosystems. Regarding the latter, an interesting development is the estimation and application of econometrically estimated transition probabilities among land cover classes (Haim et al., 2011; Radeloff et al., 2012), and their ability to be recast as CET supply functions for land allocation (Ahmed et al., 2008). In the short run a tractable alternative is to adjust the AEZ-specific land endowments parametrically, by constructing scenarios that exogenously prescribe the balance between arable land gains from ecosystem conversion versus losses to urban encroachment.

4.9 Sea Level Rise

70. Increasing sea height is one of the least scientifically controversial climate impacts, but one which is subject to considerable uncertainty, mainly due to thermal stability of glaciers and ice sheets (e.g., Bamber and Aspinall, 2013; Nick et al., 2013). Sea level rise has the potential to adversely affect all economic activities that are located in low-lying coastal zones. The information necessary to capture the impacts is the extent of vulnerable areas within regions in each time period, and the mix of production and consumption within these zones. In principle, the latter can be estimated by combining national accounts

with administrative-level data on business composition and gridded high-resolution proxies for activity such as the GEcon or DMSP/VIIRS Nighttime Lights datasets (Nordhaus, 2006; Chen and Nordhaus, 2011; Henderson et al., 2012; Nordhaus and Chen, 2012). As well, the vulnerability of coastal grid cells can be classified using GIS techniques to spatially join them with coastal impact databases such as DIVA (Vafeidis et al., 2008), or engineering-based structure flood damage relationships of the type incorporated with the HAZUS model (e.g., Klima et al., 2012).

71. Global-scale assessment efforts must also confront two challenges that are likely to remain intractable without additional fundamental data. First, over large areas the vertical resolution of topographic data is too coarse to enable the depth and horizontal extent of inundation to be accurately captured. For example, the NASA Shuttle Radar Topography Mission (SRTM v. 2) 90% confidence interval of absolute vertical error is 9m globally and less than 5m over substantial regions between 60°S and 60°N latitude, but outside this range the finest vertical resolution (USGS' Global Land One-km Base Elevation (GLOBE) database) is 30m! Second, increased erosion from wave action and capital stock destruction from overland penetration of storm surges are more likely to be responsible for damage than land loss from sea height itself. For this reason it is all too easy to draw misleading conclusions from analyses which stop at calculating the magnitude of cell-level capital stock damage or business interruption loss for a given intensity of storm. Risk assessments should be undertaken that combine estimates of "one-off" damage with region-specific shifts in the probability of storm events to generate distributions of land loss and business interruption shocks on decadal scales. However, without improved understanding of regional storm probabilities' predictability and relationship to radiative forcing, such estimates must inevitably be constructed based on a mix of judgment and assumptions. These issues are touched on further in the next section's discussion of extreme events.

4.10 Extreme Events

72. Events related to extreme weather conditions, such as floods, severe storms and forest fires are characterised by limited spatial extent and short duration.[21] This complicates the incorporation of such events in large scale global assessments, which look at longer term trends. Nevertheless, there have been attempts to assess the macroeconomic costs of extreme weather events. An emerging trend in the natural hazards literature is to couple process simulations forced by scenarios of a particular event with spatially detailed CGE models of regional economies, using decision support tools such as HAZUS to translate endpoints such as inundation depth into damage to buildings and their contents (see, e.g., Porter et al., 2010). In addition to direct infrastructure and capital stock losses, transitory productivity declines in sectors affected by "business interruption" (due to input shortages, loss of utility lifelines, loss of labour due to mortality, evacuation or longer-term displacement, and other features of the chaotic post-disaster economic environment - see, e.g., Rose 2004, 2007; Rose and Lim, 2002) trigger a host of general equilibrium adjustments which result in forgone output. An issue that arises here is the need to resolve damage to specific types of assets, something which is not adequately captured by models with "jelly" capital that is frictionlessly reallocated among sectors. For this reason it is necessary to have some representation of sector-specific capital stocks which exhibit sluggish adjustment. The latter can be implemented by using a short (e.g., sub-annual) time-step for model simulations, but doing so raises questions about CGE models' ability to capture the disequilibrium influences that may be important determinants of economic losses at these time-scales.

73. Following from the discussion in Section 4.9, although it is relatively straightforward to specify and simulate the effects of a "one-off" extreme event scenario in a single region, it is challenging to translate these into shocks at broader scales in a way that adequately captures risk. The fact that most IAMs solve on time-steps of years to decades means that events with a 500- or even 100-year return frequency

[21] Long-term drought is a fundamentally different type of impact, and is dealt with in Section 4.5.

occur with very low probability, with the result that the expected value of shocks at a given time step may be negligibly small. This problem can be exacerbated by spatial uncertainty, in the form of diffuse probability distributions for the occurrence of large-magnitude events over the comparatively large geographic area of most IAM regions.

74. Even for the one-off case, integrated assessments can founder on a lack of critical input data across a wide geographic area. For example, lacking a comprehensive hydrological model with which to simulate the inland flood impacts of a severe storm at fine spatial scales, Porter et al. (2010) were forced to approximate inundation depth and duration from GCM-generated runoff for individual watersheds by combining expert judgment with flood insurance maps. By contrast, Feyen et al.'s (2012) Europe-wide overland flood assessment is made possible by the availability of a large-scale hydrological simulation, regional climate model outputs to generate spatially resolved estimates of river discharge, a high-resolution digital elevation model that enabled the use of a planar approximation to translate river depth exceedances of bank heights into inundation extents and depths, and country-specific land use data and flood depth-damage functions which facilitate transformation of flood depths into spatially resolved direct monetary damage estimates.

4.11 Ecosystems, Biodiversity, and Ecosystem Services

75. Ecosystems interact with human societies through a variety of channels that are pervasive, but complex and poorly understood.[22] As catalogued in Table 4 in Annex I, ecosystem services affect the quality of arable land and fresh water, the productivity of managed ecosystems used to produce food, fuel, wood and fibre, species diversity that serves as a genetic resource for biotechnology, the supply of natural amenities that form the basis for tourism, cultural heritage and plethora of non-market benefits, and habitats that help buffer coastal settlements and infrastructure against damage from cyclones and sea level rise. But despite this scoping analysis, fundamental gaps in scientific understanding continue to hamper efforts to drill down beneath these broad categories to elaborate in any detail the chain of linkages from climate variables' effects on ecosystem structure and functioning to changes in service flows to impacts on affected economic activities (outside of perhaps agriculture and forestry). Nearly a decade after the landmark study by Schröter et al. (2005) the first link is still the focus of much of the natural science literature. Attempts to translate this growing body of knowledge into implications for ecosystem services are comparatively recent, and are at a very preliminary stage (e.g., Kumar, 2012).

76. The extent of the challenge faced by IA modelling is apparent from studies such as Bosello et al. (2011), whose consideration of services is restricted to yields in agriculture and forestry and carbon storage in terrestrial biomass: food, fuel, fibre and climate regulation in the taxonomy of Table 4. The dependence of various economic activities on the remaining provisioning and regulating services has not been explored. Indeed, the examples highlighted in Table 3 indicate that these services are likely to modulate the economic effects of other impact categories considered in this section, amplifying or attenuating the influence of various endpoints in ways that are context-dependent. In agriculture and forestry, the observed dependence of the productivity of managed ecosystems on climate variables invariably incorporates some or all of the responses of natural processes of nutrient cycling, life cycles of pathogenic organisms and biological pest control. Similarly, declining health and extent of wetland ecosystems reduces their ability to shield infrastructure and settlements from the effects of extreme storm events such as overland runoff pulses or coastal or riverine surges. In these examples, climate change-induced attenuation of beneficial ecosystem processes worsens yield shocks and capital stock damage, respectively. Adverse effects on the productivity and extent of ecosystems in water catchment areas can lead to reductions in both the quantity and quality of surface water resource inputs to the water distribution sector, exacerbating the supply shock in Figure 6 relative to changes in runoff that are purely due to precipitation. Lastly, the combined effect of

[22] Table 5 in Annex I introduces the main taxonomy and examples for ecosystem services.

poleward expansion in the range of warm-water marine species and habitat loss for cold-water species has an ambiguous impact on fishery resources which is likely to be highly location- and species dependent.

77. With regard to cultural services, ecosystems in many areas of the world are instrumental in supplying natural amenities that are important sources of tourism revenue. The problem for analysis is that the relationship between such amenities' attractiveness to tourists and the scope and form of their biodiversity has not been systematically characterized. The current state of the art is to treat amenities as latent in econometric models of cross-country tourist demand, instead specifying arrivals (Hamilton et al., 2005a) or stays (Amelung and Moreno, 2012) as a function of climatic variables and land area, and the resulting estimates used to construct climate response functions that scale tourism demand with changes in temperature or land-loss due to sea-level rise (Bigano et al., 2008). A first step toward imputing the derived demand for amenities might be to develop summary statistics of the ecological and non-ecological characteristics of protected areas,[23] aggregate these by country, and investigate their performance as covariates in the regression framework above. Success in this initial phase could then pave the way to link assessments of ecological characteristics' climate responses to shifts in tourism flows.

5. Concluding Remarks

78. This report has reviewed key integrated assessment methodologies for quantifying the economic costs of climate change impacts. Conceptual frameworks were introduced to classify the effects of impacts, rigorously evaluate climate damages, and understand the origins and consequences of the unavoidable overlap between damages and the costs of climate adaptation. These were developed into a canonical IA framework that was used to guide the evaluation of existing modelling approaches and their results, and to survey options for modelling key endpoints related to economically relevant impacts categories, and their connections with various sectors.

79. Overall, existing IAMs have a long way to go to meet the challenges of modelling climate impacts and adaptation. Although CGE models are generally well positioned to capture the regional and sectoral specificity of impacts' connections with the economy, many models simply do not have the level of detail necessary to overcome issues of aggregation bias. And even though CGE models can and do capture the effects of passive adaptation through market adjustments, much of the groundwork is yet to be laid to assess the costs and benefits of deliberate adaptive/coping and protective/defensive adaptation expenditures. Underlying these issues is the problem of fundamental data gaps that militate against specification of the relationships between climate change and impact endpoints at regional scales. It is common to find a patchwork of empirically-based indicators that imperfectly align with impact endpoints and their knock-on shocks to economic sectors, and modellers must often make heroic efforts to translate these disparate sources of information into a form that can be incorporated into IAMs. This report has made some progress in enumerating economically important endpoints and elaborating methods for modelling the channels through which they affect sectors within IAMs. Notwithstanding this, the key research need is to bridge the gap between the model representations outlined here and empirical studies of the corresponding climate-endpoint responses. Such a program of investigation should be a priority for the IA community.

[23] A potentially useful data source is the World Protected Areas List (http://protectedplanet.net)

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ANNEX I: MODELLING CLIMATE CHANGE IMPACTS

Table 4. Climate impacts: biophisical endpoints, economic sectors and modelling strategies

"Impact Sector"	Sectors/ Activities	Impact Endpoints	Economic Manifestation	Modelling Strategies and Options*
Agriculture	Crop sectors	-Drought -Heat stress -Shift in crop suitability zones	Reduced crop productivity/yields	-Simple: Neutral productivity shock to crop sector cost functions [YP] -Nuanced: Biased productivity shock to land or land-water fixed-factor resource input to agriculture sector [RP]
	Livestock sector	Heat stress	Reduced productivity	Neutral productivity shock to sectoral cost function [YP]
Fisheries	Fisheries sectors	Shift in marine habitat	Reduced yields	-Simple: Neutral productivity shock to fishery sector cost function [YP] -Nuanced: Biased productivity shock to habitat fixed-factor resource input to fisheries sector [RP]
Energy Supply	Primary energy supply sectors	Fresh water scarcity	-Reduction in cooling water withdrawals -Reduction in hydroelectric generation	-Simple: Neutral productivity shock to energy supply sector cost functions [YP] -Nuanced: Biased productivity shock to fixed-factor input to energy supply sectors [RP]
		Increased ambient temperatures	Reduction in thermoelectric generation efficiency	-Simple: Neutral productivity shock to electric power sector cost function [YP] -Nuanced: Biased productivity shock to fuel inputs to electric power [IP]
Energy Use	Non-energy sectors Household sector	-Increased cooling demands -Decreased heating demands	Secular increase in overall demand for energy	Secular shifts in energy demand functions and energy productivity in sectors' cost/households' expenditure functions [IP]
Water Resources	Marketed water sector	Drought	Reduction in output	-Simple: Neutral productivity shock to water supply sector cost function [YP] -Nuanced: Biased productivity shock to endowment of fixed-factor resource input to water supply sector [RP]
	Agriculture	Drought	-Reduction in non-marketed water -Reduction in irrigation	-Simple: Neutral productivity shock to agriculture sector cost function [YP] -Nuanced: Neutral productivity shock to irrigation subsector [YP]
Human Health	Aggregate labor supply	Increased morbidity/ mortality due to	Reduction in labor supply/productivity	Reduction in baseline rate of labor productivity increase [LP]

	Household sector	disease, heat stress	Secular increase in healthcare demand	Secular shifts in healthcare demand functions and productivity of healthcare input to households' expenditure functions [IP]
Transportation	Marketed transport services	Damage to infrastructure from sea level rise and extreme events	Reduction in output Capital stock destruction	Best modelled under Extreme Events and Sea Level Rise
	Household own-supplied transport			
Forestry/ Land Use/ Land Cover Change	Forestry sectors	Fires	Reduction in output Capital stock destruction	Best modelled under Extreme Events
		CO2 fertilization/woody encroachment	Increase in output	-Simple: Neutral productivity shock to forestry sector cost function [YP] -Nuanced: Biased productivity shock to fixed-factor or land input to forestry sector [RP]
		Shift in crop suitability zones	Reduction in productivity	
Sea Level Rise	All sectors	-Inundation -Abandonment/defense of coastal lowland areas	-Reduced land/capital endowment -Increase in coastal protection expenditure	-Simple: Neutral productivity shocks in all sectors, differentiated according to potential for exposure [YP] -Nuanced: Reduction in supply of land, mandated increase in non-productive defensive investments in exposed sectors [RS, KS]
Extreme Events	All sectors	-Floods -Hurricanes -Forest fires	Capital stock destruction Business interruption	-Simple: Neutral productivity shocks in all sectors, differentiated according to severity of impact and potential for exposure [YP] -Nuanced: Reduction in endowments of labor and sector-specific capital [LS, KS]
Ecosystems/ Biodiversity/ Ecosystem Services	Fisheries sector	Marine habitat loss/ ecosystem disruption	Reduction in yields	Best modelled under Fisheries
	Agriculture/ Forestry sectors	Increasing virulence of pathogenic species	Reduction in yields	Best modelled under Agriculture and Forestry
	Tourism/Household sectors	Nature-based recreation and tourism	Reduction in supply of non-market amenities	-Simple: Neutral productivity shock in tourism sector [YP] -Nuanced: Biased productivity shock to "natural capital" fixed-factor input to tourism sector [RP]; Reduction in endowment of "natural amenity" fixed-factor consumed by household [RS]
	All sectors	Coastal hazard reduction	Capital stock protection	Best modelled under Extreme Events (Hurricanes, Floods)
	Marketed water sector	Reduced water supply/quality	Reduction in output	Best modelled under Water Resources

* Codes in square braces correspond to taxonomy of impact effects introduced in Figure 2.

Source: authors drawing on the literature.

Table 5. Ecosystem services: taxonomy and examples

Provisioning services	Regulating services	Cultural services	Supporting/Habitat services
Products gained from ecosystems	Material and nonmaterial benefits obtained from regulation of environmental conditions	Nonmaterial benefits obtained from ecosystems through spiritual enrichment, intellectual development, reflection, recreation, and aesthetic experiences	Necessary for the production of all other ecosystem services
• Food (all food products derived from plants, animals, and microbes) • Fuels (fuelwood and modern biofuel crops) • Freshwater (as water supply for households, industry, agriculture, and other water-using sectors, and as habitat for the freshwater fishery) • Fiber (materials such as wood, jute, hemp, silk, and several other products) • Genetic resources (genetic information used for animal and plant breeding and biotechnology) • Biochemicals, natural medicines, pharmaceuticals, and ornamental resources	• Climate regulation (through modulation of the carbon cycle and other aspects of the climate system by ecosystems) • Erosion control (through soil retention) • Air quality maintenance (through absorption of harmful substances by ecosystems) • Water regulation and water purification (through mitigating effects of ecosystems on extremes of runoff and accumulation of harmful substances) • Human disease control (through ecosystem control of the spread of human disease vectors) • Biological pest and disease control (through ecosystem control of the spread of crop pests and pathogens) • Pollination (through influences of ecosystems on the abundance and distribution of pollinators); and • Coastal protection (through the protecting effect of ecosystems, such as coral reefs and mangroves, on coastal structures)	• Cultural heritage • Aesthetic values • Opportunities for recreation and tourism (including ecotourism) • Inspiration for culture, art and design • Spiritual experience • Resources for educational and intellectual development	• Maintenance of life cycles of migratory species (including nursery services) • Maintenance of genetic diversity (especially in gene pool protection)

Source: Millenium assessment (2003); Alcamo et al. (2005); Kumar (2012)

ANNEX II: THE PESETA STUDY OF CLIMATE IMPACTS ON EUROPE IN 2050

Table 6. Climate impact shocks (input) to European regional economies in the PESETA study

	2.5°C	3.9°C	4.1°C	5.4°C	5.4°C High SLR
A. Agriculture (% Change in Yields)					
Northern Europe	37	39	36	52	
British Isles	-9	-11	15	19	
Central Europe North	-1	-3	2	-8	
Central Europe South	5	5	3	-3	
Southern Europe	0	-12	-4	-27	
EU	3	-2	3	-10	
B. River Floods (Million 2004 euro)					
Total economic damage					
Northern Europe	-325	20	-100	-95	
British Isles	755	2,854	2,778	4,966	
Central Europe North	1,497	2,201	3,006	5,327	
Central Europe South	3,495	4,272	2,876	4,928	
Southern Europe	2,306	2,122	291	-95	
EU	7,728	11,469	8,852	15,032	
Damage to residential buildings					
Northern Europe	-278	-13	-75	-86	
British Isles	676	2,330	2,330	4,134	
Central Europe North	1,224	1,703	2,309	4,180	
Central Europe South	2,938	3,625	2,439	4,203	
Southern Europe	1,870	1,661	228	-70	
EU	6,429	9,306	7,231	12,360	
C. Tourism (Million 2005 euro)					
Northern Europe	443	642	1,888	2,411	
British Isles	680	932	3,587	4,546	
Central Europe North	634	920	3,291	4,152	
Central Europe South	925	1,763	7,673	9,556	
Southern Europe	-824	-995	-3,080	-5,398	
EU	1,858	3,262	13,360	15,268	
D. Coastal Systems (Million 1995 euro)					
Migration costs					
Northern Europe	17	39	49	84	927
British Isles	0	11	0	11	12,959
Central Europe North	907	812	950	722	1,327
Central Europe South	81	341	162	482	2,082
Southern Europe	827	1,647	1,190	1,352	7,853
EU	1,831	2,850	2,351	2,651	25,149
Maritime inundation costs					
Northern Europe	562	594	577	638	889
British Isles	1,827	1,978	1,871	2,066	2,776
Central Europe North	9,320	10,114	9,547	10,380	12,306
Central Europe South	694	758	716	782	1,064
Southern Europe	849	904	865	921	1,200
EU	13,251	14,348	13,575	14,786	18,235

Source: Ciscar et al. (2012).

Table 7. Macroeconomic costs of climate impacts to European regions in the PESETA study

European regions*	Southern Europe	Central Europe South	Central Europe North	British Isles	Northern Europe	EU
Economic impacts as estimated by the agriculture model						
Welfare Change (%)‡						
2.5°C	-0,05	0,06	0,01	-0,09	0,58	0,01
3.9°C	-0,37	0,02	-0,05	-0,11	0,59	-0,10
4.1°C	-0,15	-0,01	0,04	0,09	0,56	0,02
5.4°C	-1,00	-0,27	-0,19	0,06	0,72	-0,32
GDP Change (%)‡						
2.5°C	-0,13	0,11	-0,02	-0,10	0,81	0,02
3.9°C	-0,52	0,06	-0,06	-0,11	0,85	-0,09
4.1°C	-0,22	-0,00	0,05	0,12	0,76	0,04
5.4°C	-1,26	-0,28	-0,17	0,16	1,09	-0,29
Economic impacts as estimated by the river flooding model						
Welfare Change (%)‡						
2.5°C	-0,13	-0,16	-0,04	-0,06	0,09	-0,08
3.9°C	-0,11	-0,25	-0,09	-0,21	0,01	-0,14
4.1°C	-0,09	-0,15	-0,13	-0,20	0,07	-0,13
5.4°C	-0,14	-0,31	-0,24	-0,37	0,10	-0,24
GDP Change (%)‡						
2.5°C	-0,01	-0,01	-0,00	0,00	0,00	-0,01
3.9°C	-0,01	-0,01	-0,01	-0,01	-0,00	-0,01
4.1°C	-0,00	-0,01	-0,01	-0,01	0,00	-0,01
5.4°C	0,00	-0,01	-0,02	-0,02	0,00	-0,01
Economic impacts as estimated by the coastal system model						
Welfare Change (%)‡						
2.5°C	-0,07	-0,06	-0,27	-0,17	-0,13	-0,16
3.9°C	-0,11	-0,08	-0,29	-0,19	-0,14	-0,18
4.1°C	-0,09	-0,06	-0,28	-0,18	-0,14	-0,17
5.4°C	-0,10	-0,09	-0,30	-0,20	-0,15	-0,18
5.4°C High Range IPCC SLR (88 cm)	-0,38	-0,19	-0,37	-1,02	-0,35	-0,46
GDP Change (%)‡						
2.5°C	-0,05	-0,05	-0,38	-0,23	-0,11	-0,19
3.9°C	-0,05	-0,05	-0,41	-0,24	-0,12	-0,20
4.1°C	-0,05	-0,05	-0,39	-0,23	-0,11	-0,20
5.4°C	-0,05	-0,05	-0,42	-0,25	-0,13	-0,21
5.4°C High Range IPCC SLR (88 cm)	-0,04	-0,06	-0,50	-0,26	-0,16	-0,24
Economic impacts as estimated by the tourism model						
Welfare Change (%)‡						
2.5°C	-0,02	0,02	0,01	0,01	0,01	0,00
3.9°C	-0,03	0,03	0,01	0,01	0,02	0,01
4.1°C	-0,08	-0,11	0,03	0,05	0,07	-0,02
5.4°C	-0,12	0,18	0,04	0,06	0,08	0,04
GDP Change (%)‡						
2.5°C	-0,01	0,00	0,00	0,00	0,00	0,00
3.9°C	-0,01	0,01	0,00	0,00	0,01	0,00
4.1°C	-0,03	-0,03	0,01	0,01	0,02	-0,01
5.4°C	-0,05	0,03	0,02	0,01	0,02	0,01

**European regions: Southern Europe (Portugal, Spain, Italy, Greece, and Bulgaria), Central Europe South (France, Austria, Czech Republic, Slovakia, Hungary, Romania, and Slovenia), Central Europe North (Belgium, The Netherlands, Germany, and Poland), British Isles (Ireland and UK), and Northern Europe (Sweden, Finland, Estonia, Latvia, and Lithuania). ‡Household welfare and GDP are compared to the 2010 values of the baseline scenario.*

Source: Ciscar et al. (2009)

ANNEX III: ICES MODEL IMPACTS ON MACROECONOMIC REGIONS

Table 8. Climate impact shocks (inputs) to world regions in the ICES model

	A. Energy			B. Tourism		C. Sea-Level Rise	D. Forestry	E. Agriculture
	Gas	*Oil*	*Electricity*	*Demand for Market Services*	*Regional Income**	*Land and capital endowments*	*NPP*	*Land productivity*
USA	0.83	1.78	7.25	2.99	0.067	-0.082	-10.73	-7.54
Mediterranean Europe	0.15	0.79	6.91	-1.18	-0.008	-0.008	-17.78	-12.60
N. Europe	-0.55	0.15	0.33	1.57	0.012	-0.258	-10.71	11.41
E. Europe	0.41	1.30	0.15	0.13	0.0007	-0.003	-9.88	-0.94
Former USSR	0.17	2.18	-2.94	5.15	0.061	-0.080	0.31	4.17
Korea/S. Africa/Australia	0.80	1.63	3.60	0.20	0.004	-0.013	-15.72	-4.01
Canada/Japan/New Zealand	0.43	1.10	8.05	8.29	0.038	-0.332	0.29	5.30
N. Africa	-0.26	0.77	7.38	-3.78	-0.018	-0.005	28.57	-21.63
Middle East	1.00	2.66	5.86	-2.71	-0.001	-0.272	-20.29	-6.53
Sub-Saharan Africa	-0.14	0.91	4.53	-2.93	-0.002	-0.034	-13.30	-8.60
S. Asia incl. India	1.94	3.06	9.46	0.01	0.0002	-0.660	-10.07	-14.22
China	-0.59	0.96	5.22	-3.32	-0.005	-0.0004	-5.87	4.07
E. Asia	-1.25	0.29	12.68	-3.28	-0.027	-0.140	-14.37	-16.03
Latin & Central America	-0.54	0.23	11.95	-2.28	-0.122	-0.027	-13.87	-3.23

	F. Health	G. River floods					
	Labor productivity	*Labor productivity*	*Agriculture (Land endowment)*	*Industry (Capital productivity)*	*Transport (Capital productivity)*	*Residential (Capital productivity)*	*Commerce (Capital productivity)*
Mediterranean Europe	-0.31	-0.0003	-0.014	-0.004	-0.003	-0.044	-0.001
N. Europe	-0.004	-0.0004	-0.013	-0.008	-0.006	-0.115	-0.002
E. Europe	-0.14	-0.0004	-0.008	-0.01	-0.01	-0.697	-0.004

Source: Bosello et al. (2012a,b) ; * Trillion dollars.

Table 9. Macroeconomic costs of climate impacts to world regions in the ICES model

	Energy Demand	Tourism	Sea-Level Rise	River Floods	Agriculture	Forestry	Health	All Impacts
USA	-0.01	0.18	-0.05	0.0009	0.05	-0.001	0.003	0.17
Mediterranean Europe	-0.05	0.07	-0.03	-0.0078	0.07	-0.008	-0.193	-0.15
N. Europe	-0.07	0.15	-0.11	-0.0121	0.23	-0.003	0.001	0.18
E. Europe	-0.02	0.10	-0.04	-0.0478	-0.15	-0.026	-0.030	-0.21
Former USSR	0.01	0.32	-0.03	0.0014	0.49	0.005	0.004	0.81
Korea/S. Africa/ Australia	-0.04	0.15	-0.04	0.0013	0.01	0.002	0.005	0.09
Canada/Japan/ New Zealand	-0.02	-0.10	-0.16	0.0011	0.19	0.004	0.004	-0.09
N. Africa	-0.03	-0.54	-0.02	0.0010	-2.10	0.009	0.005	-2.67
Middle East	-0.19	-0.42	-0.10	0.0010	-0.10	-0.034	0.004	-0.83
Sub-Saharan Africa	0.00	-0.31	-0.02	0.0005	-1.09	-0.097	0.003	-1.50
S. Asia incl. India	0.22	0.04	-0.32	0.0002	-3.02	-0.018	0.002	-3.10
China	0.04	-0.24	-0.03	0.0005	0.43	-0.004	0.003	0.20
E. Asia	0.01	-0.36	-0.10	0.0005	-2.36	-0.025	0.002	-2.82
Latin & Central America	-0.04	-0.49	-0.05	0.0014	-0.11	-0.014	0.005	-0.71
World	-0.01	-0.12	-0.07	-0.0019	-0.28	-0.011	-0.008	-0.50
EU total	-0.06	0.12	-0.07	-0.0165	0.11	-0.008	-0.067	0.01

Source: Bosello et al. (2012b)