Valuing climate impacts in integrated assessment models: the MIT IGSM

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Abstract We discuss a strategy for investigating the impacts of climate change on Earth's physical, biological and human resources and links to their socio-economic consequences. As examples, we consider effects on agriculture and human health. Progress requires a careful understanding of the chain of physical changes—global and regional temperature, precipitation, ocean acidification, polar ice melting. We relate those changes to other physical and biological variables that help people understand risks to factors relevant to their daily lives—crop yield, food prices, premature death, flooding or drought events, land use change. Finally, we investigate how societies may adapt, or not, to these changes and how the combination of measures to adapt or to live with losses will affect the economy. Valuation and assessment of market impacts can play an important role, but we must recognize the limits of efforts to value impacts where deep uncertainty does not allow a description of the causal chain of effects that can be described, much less assigned a likelihood. A mixed approach of valuing impacts, evaluating physical and biological effects, and working to better describe uncertainties in the earth system can contribute to the social dialogue needed to achieve consensus on the level and type of mitigation and adaptation actions.

1 Introduction

Integrated assessment models (IAMs) have proven useful for analysis of climate change because they represent the entire inhabited earth system, albeit typically with simplified

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model components. Valuation of impacts poses several challenges. Existing climate varies dramatically across the globe, and so how changes in precipitation, temperature and extremes will affect systems in different places varies widely. Warming may mean more frost-free days in some locations – generally expanding potential for agriculture – while pushing temperatures beyond critical thresholds in other regions. More precipitation may be beneficial to drier areas, but an increase in heavy downpours can have very damaging effects – eroding soils and contributing to flash floods – even in areas that might benefit from more precipitation. Even if there is no change in precipitation over the year, but longer periods between events as suggested by general circulation models (GCM) results, can lead to more of both damaging droughts and more flooding. Thus, impacts work requires relatively finely-detailed spatial resolution.

There are 3 broad challenges for valuing damages in IAMs: Computational feasibility, uncertainty and "deep" uncertainty, and valuing physical changes. Briefly:

(1) Computational feasibility. Highly resolved climate models are computationally de-manding, and the best models for representing crop growth, water resource manage-ment, or coastal infrastructure are already computer intensive when used at a specific site or region. Operating such models for tens of thousands of grid cells is often not possible. Clever simplification of these models is needed to retain the basic responses over the range of potential climate impacts.

(2) Uncertainty and "deep" uncertainty. Uncertainty in climate projections is critical, and long tails of distributions can mean that outcomes where the likelihood of occurrences is very small may contribute far more to expected damage if the effects of such outcomes are truly catastrophic then the other 99 % of the distribution of likely outcomes. We can characterize known uncertainties and conduct Monte Carlo studies to estimate likelihoods, but the hundreds of scenarios compound the computational demands (e.g. Sokolov, et al. 2009). The presence of deep uncertainty—the very likely prospect of completely unknown relationships in the earth system—is more difficult to address (e.g. Weitzman 2009). As we observe the climate changing, we have already been surprised by impacts we did not expect. Arctic ice seems to be disappearing faster than models would have predicted. The Greenland and West Antarctic ice sheets – once thought to be fairly stable – are now seen as more fragile, but due to processes not fully understood or yet modeled (e.g. Chen et al. 2006). And only after the fact were we able to see that outbreaks of pests, such as the spruce budworm in western North America, were at least partly due to climate change (e.g. Volney and Fleming 2000) or more broadly the complexities of pest interactions (Harrington, et al. 1999).

(3) Valuation of physical effects. Valuation of crop yield loss, or even some ecosystem services, is fairly straightforward and can be based on market data (e.g. Antoine, et al. 2008). But many ecosystem services are hard to value with much confidence (Carpenter, et al. 2006). Contingent valuation methods that obtain willingness to pay estimates are controversial even for well-defined environmental goods, but when experts do not fully understand how human existence depends on the functioning of these systems surveys the general population are unlikely to reveal these values.

These considerations have led us to be relatively cautious about claiming to reduce all impacts to a dollar value. Our solution is to describe the chain of physical changes—global and regional temperature, ocean acidification, polar ice melting—and relate those to other physical and biological variables that help people understand risks to factors more relevant to their daily lives—crop yield, food prices, premature death, flooding or drought events,

required land use change—and then finally how societies may adapt, or not adapt, to these changes and how the combination of measures to adapt or to live with losses will affect the economy. An aggregate welfare change is an output of our economic model, but at this point we have not completed work to fully integrate even those damages we think we understand. Meanwhile, how the economic and social system might respond to extreme changes in climate is also not well understood.

The paper is organized in the following way. Section 2 describes the structure of the MIT IGSM framework. Section 3 describes our approach to valuation within our computable general equilibrium (CGE) model and unfinished business in terms of valuing broader effects of climate change. Section 4 focuses on representation of uncertainty, and Section 5 concludes.

2 The current structure of the MIT integrated framework

The MIT IGSM framework has been developed to allow flexibly assembly of earth system models of variable resolution and complexity. Human activities as they contribute to environmental change or are affected by it are represented in multi-region, multi-sector model of the economy that solves for the prices and quantities of interacting domestic and international markets for energy and non-energy goods as well as for equilibrium in factor markets, with the main component being the MIT Emissions Predictions and Policy Analysis (EPPA) model (Paltsev et al. 2005). The standard atmospheric component is a 2-D atmospheric (zonally-averaged statistical dynamics) model based on the Goddard Institute for Space Studies (GISS) GCM. IGSM version 2.2 couples this atmosphere with a 2-D ocean model (latitude, longitude) with treatment of heat and carbon flows into the deep ocean (Sokolov et al. 2005). Modeling of atmospheric composition for the 2-D zonal-mean model uses continuity equations for trace constituents solved in mass conservative or flux form for 33 chemical species (Wang et al. 1998). A reduced-form urban chemical model that can be nested within coarser-scale models has been developed and implemented to better represent the sub-grid scale urban chemical processes that influence air chemistry and climate (Cohen and Prinn 2009). This is critical both for accurate representation of future climate trends and for our increasing focus on impacts, especially to human health and down-wind ecosystems. The Global Land System component (GLS, Schlosser et al. 2007) links biogeophysical, ecological and biogeochemical components including: (1) the National Center for Atmospheric Research (NCAR) Community Land Model (CLM), which calculates the global, terrestrial water and energy balances; (2) the Terrestrial Ecosystems Model (TEM) of the Marine Biological Laboratory, which simulates carbon (CO_2) fluxes and the storage of carbon and nitrogen in vegetation and soils including net primary production and carbon sequestration or loss; and (3) the Natural Emissions Model (NEM), which simulates fluxes of CH_4 and N_2O, and is now embedded within TEM. We then link econometrically-based decisions regarding the spatial pattern of land use (from EPPA) and land conversion (from TEM) to examine impacts of land use change and greenhouse gas fluxes (Melillo et al. 2009; Gurgel et al. 2011; Reilly et al. 2012). Recently, we have adapted and developed a series of models to link the natural hydrological cycle to water use (Strzepek et al. 2010; Hughes et al. 2010). IGSM version 2.3 (where 2.3 indicates the 2-D atmosphere/full 3-D ocean GCM configuration) (Sokolov et al. 2005; Dutkiewicz et al. 2005) is thus an Earth system model that allows simulation of critical feedbacks among its various components, including the atmosphere, ocean, land, urban processes and human activities.

A limitation of the IGSM2.3 in the above 2-D (zonally averaged) atmosphere model is that regional (i.e. longitudinal) detail necessary for impact analysis does not exist. In early

studies we used current patterns scaled by latitudinal changes. We now use the NCAR Community Atmosphere Model (CAM), driven by the IGSM2.3 sea surface temperature anomalies and greenhouse gases (GHGs) and aerosol concentrations (Monier et al. 2012). New modules were developed and implemented in CAM to change its climate sensitivity through cloud radiative adjustment (Sokolov and Monier 2012). The IGSM-CAM framework provides us with the capability to study global and regional climate change where climate parameters can be modified to span the range of uncertainty and various emissions scenarios can be tested as in Fig. 1.

3 Valuing "non-market" impacts in a general equilibrium framework

Changes in climate are "non-market" in the sense that these changes are not directly priced anywhere. However, the non-market valuation literature has made much use of the fact that the non-market changes have traces in market goods. As noted at the outset, our efforts to incorporate damages are incomplete. Here we describe our basic approach to valuation and include two examples: economy-atmosphere-land-agriculture interactions and air pollution health effects. We integrate the climate effects into the economic component of the MIT IGSM framework, namely the MIT EPPA model (Paltsev et al. 2005). The underlying approach we use is based on identifying where within each country's or region's Social Accounting Matrix (SAM) damages will be observed. The information contained in the SAM is the basis for the creation of a CGE model (Rutherford and Paltsev 1999). A SAM describes the flows among the various sectors of the economy, and we expand it to represent household activities to capture damages that are not fully reflected in market outcomes
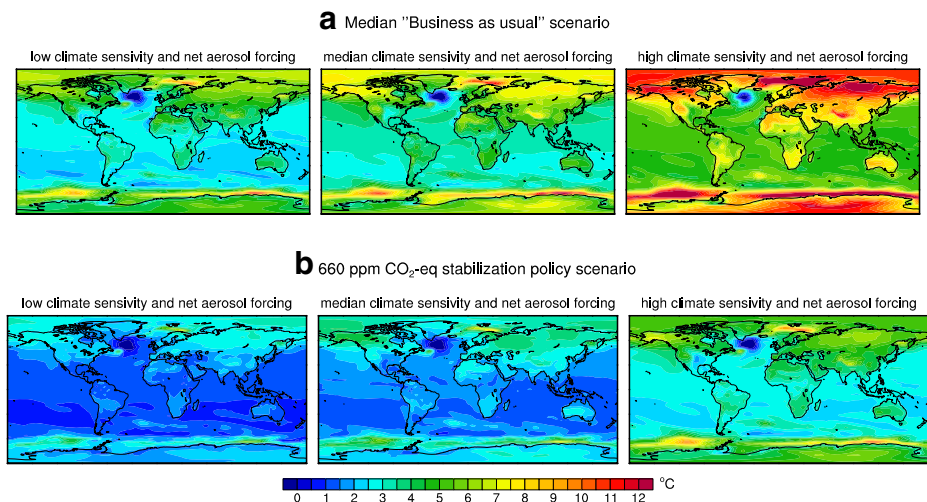

a Median "Business as usual" scenario

low climate sensitivity and net aerosol forcing   median climate sensitivity and net aerosol forcing   high climate sensitivity and net aerosol forcing

b 660 ppm CO_2-eq stabilization policy scenario

low climate sensitivity and net aerosol forcing   median climate sensitivity and net aerosol forcing   high climate sensitivity and net aerosol forcing

°C
0 1 2 3 4 5 6 7 8 9 10 11 12

Fig. 1 Surface air temperature changes between 1980 and 2000 and 2080–2100 based on the MIT IGSM-CAM framework for two emissions scenarios and three sets of climate parameters. The two emissions scenarios are a median "business as usual" scenario where no policy is implemented after 2012 and a policy scenario where greenhouse-gases are stabilized at 660 ppm of CO_2-equivalent by 2100. The ocean heat uptake rate is fixed at 0.5 cm^2/s in all six simulations. The three sets of climate parameters chosen are a low climate sensitivity (CS) and net aerosol forcing (Fae) case (CS=2.0 °C and Fae=−0.25 W/m², a median case (CS= 2.5 °C and Fae=−0.55 W/m²) and a high case (CS=4.5 °C and Fae=−0.85 W/m²)

(Fig. 2). It represents the value of economic transactions in a given period of time. Transactions of goods and services are broken down by intermediate and final use. A SAM also shows the cost structure of production activities – intermediate inputs, compensation to labor and capital, taxes on production. As expanded, we value non-work time and so, for example, illness or death that results in losses of non-paid work time are valued.

To build a CGE model, the production technology and consumer preferences must be specified, and the key additional data elements required are elasticities of substitution between inputs in production and between goods in consumption. A SAM does not provide this information. We discuss further how our health effects and agricultural impacts components are integrated into the SAM, with examples of results, in the next sections.

3.1 Valuing health effects

The conventional approach to estimating health damage from air pollution is to multiply a predicted illness or death by a constant value meant to capture the value of lost life or the cost of the health care. However, health costs do not affect the overall economy equally. When people get sick and miss work, their lost productivity will negatively affect certain sectors. In addition, people buy medicine and use medical services, an expenditure that will require more resources to be used in the health sector at the expense of other sectors. People sometimes get ill, not due to air pollution levels in a single day or year, but rather due to their lifetime exposure to pollutants. If people die prematurely due to pollution exposure, their contribution to the workforce is lost in every year from their death until their normal

Fig. 2 Social Accounting Matrix expanded to include health effects of air pollution. Source: Paltsev and Reilly 2006. Added components are in bold italic

retirement date. Illness and death also result in lost non-work time of the labor force population and children, elderly and others who are not part of the paid labor force.

Extending the model to included health effects involves valuation of non-wage time (leisure) and inclusion of a household production of health services – which we represent in an extended SAM, as shown in Fig. 2, with the extensions of the model highlighted in italic bold. We add a household service sector that provides a "pollution health service" to final consumption to capture economic effects of morbidity and mortality from acute exposure. It uses "medical services" (i.e., hospital care and physician services) from the "services" sector of the EPPA model and household labor to produce a health service. The household labor is drawn from labor and leisure, and thus reduces the amount available for other uses (i.e., an illness results in the purchase of medical services and/or patient time to recover when the ill person cannot work or participate in other household activities). We use data from traditional valuation work to estimate the amount of each of these inputs for each health endpoint, as discussed in the following sections. Changed pollution levels are modeled as a Hick's neutral technical change: higher pollution levels require proportionally more of all inputs to deliver the same level of health service, or lower levels require proportionally less. Mortality effects simply result in a loss of labor and leisure, and thus are equivalent to a negative labor productivity shock. Impacts on health are usually estimated to be the largest air pollution effects when measured in economic terms using conventional valuation approaches, dominating other losses such as damage to physical infrastructure, crops, ecosystems and loss of visibility.

The health effects of air pollution present themselves as both a loss of current well-being (i.e. an illness brought on by acute exposure to air pollution that results in temporary hospitalization or restricted activity) and as an effect that lasts through many periods (i.e. years of exposure that eventually lead to illnesses and deaths, where social and economic losses extend from the point of premature death forward until that person would have died of other causes). We must therefore account both for stocks and flows of labor endowment in the economy and the population's exposure to pollution. Health effects also present them-selves as both market and non-market effects. Death or illness of someone in the labor force means that person's income is no longer part of the economy, clearly a market effect. Illness also often involves expenditure on medical services, counted as part of the market economy. Death and illness also involve loss of non-paid work time, a non-market impact. This likely involves a loss of time for household chores or a loss of time spent on leisure activities. The health effects area thus is both a large component of total air pollution damages and provides an opportunity to develop methods to handle a variety of issues faced in valuing changes in environmental conditions.

Epidemiological relationships have been estimated for many pollutants, as they relate to a variety of health impacts from restricted activity days, cases of asthma for different age groups, and susceptibility to premature death from acute and chronic exposure to pollutants (Yang et al. 2005; Matus et al. 2008; Nam et al. 2010; and Matus et al. 2012). Here we focus on a forward-looking study on potential effects of ozone on human health, where we are able to separate the effects of increasing emissions of ozone precursors from the effects on climate on the chemistry of ozone formation (Selin et al. 2009). Because the atmospheric component of the standard IGSM is only resolved vertically and by latitude, we use published results for 2000 and 2050 ozone concentrations from the GEOS-Chem Chemical Transport Model (CTM) based on IPCC SRES scenarios to generate more realistic emissions for different regions (Wu et al. 2008a, 2008b). Our goal is to demonstrate how valuation of health impacts is accomplished within the IGSM and issues that arise. Here we focus only the effects of ozone on health. We do not adjust baseline population for other

potential climate effects on health. Since our approach is to follow the causal factors from climate through the mechanisms that lead to a variety of specific health outcomes, there is no simple way to make such adjustments, absent a complete model of these health pathways.

We found that there are areas where there are health benefits, and other areas where there are additional health costs (see Supplementary Material for additional information about the impacts). This is not surprising, as changes in climate – including increasing temperature and other changing meteorological variables – have a complex effect on ozone concentrations (Mickley 2007). While there is substantial variability among models of the climate impact of ozone, most models predict a decrease in surface ozone background due to the effect of water vapor, and surface ozone increases of 1–10 ppb driven primarily by temperature in polluted mid-latitude regions (Jacob and Winner 2009). The net effect on global welfare is less than $1 billion (year 2000 constant). The combination of some losers and some gainers emphasizes the importance of considering distributional impacts. In addition, because the economic model is a market based model, it evaluates labor loss and other costs of damage at prices relevant to each region. And so, where wages are lower, illness or death is valued at a lower wage rate. The wage rates are changing over time as the economies grow and labor productivity improves. One must thus be cautious about using the global aggregate to judge the potential value of emissions reductions, as it raises issues of interpersonal comparison of welfare among individuals in different regions. Such aggregation is justified under the Pareto-improving assumption that if climate change were avoided, and so these damages, it is possible to compensate losers so that no one is worse off. Selin et al. (2011), Matus et al. (2008, 2012), and Nam et al. (2010) investigated uncertainty in results as they relate to atmospheric chemistry models, dose–response relationships, and parameters of the economic model – an advantage of integrated approach.

3.2 Agriculture effects

Agriculture is another area where environmental change is likely to have important effects. Multiple changes that may occur over the next century will affect vegetation and thus crop, forest productivity and pasture productivity. Some of these effects are likely to be positive (e.g. CO_2 fertilization), some negative (e.g. tropospheric ozone damage), and some may be either positive or negative (temperature and precipitation). Climate effects differ across regions (i.e. more precipitation in some areas and less in others) and warming may increase growing season lengths in cold-limited growing areas while acting as a detriment to productivity in areas with already-high temperatures. For this work, we have augmented the EPPA model by further disaggregating the agricultural sector. This allows us to simulate economic effects of changes in yield (i.e. the productivity of cropland) on the regional economies of the world, including impacts on agricultural trade. In terms of the SAM in Fig. 2, we do not need to add any additional sectors—agricultural sectors already exist in the market economy. Among the value added inputs are natural resources—here cropland, pastureland, and forestland –used in market sectors (matrix G) and used in the crops, livestock, and forest sectors (in matrix A). We alter the productivity of land in these sectors based on changes in yield from the Terrestrial Ecosystem Model (TEM) component of the IGSM. A yield loss of, for example, 10 % is represented as an effective reduction of the land input by 10 % into that sector. The EPPA model includes multiple channels of market-based adaptation, including input substitution. Productivity of land in all regions is affected, and so, these are transmitted via imports shown in the SAM as matrix D. We are thus able to examine the extent to which market forces contribute toward adaptation, and modify the initial yield effects.

As an example of climate change impacts on agriculture, we examine multiple scenarios where tropospheric ozone precursors are controlled or not, and where greenhouse gas emissions are abated or not (Reilly *et al.* 2007). This allows us to consider how these policies interact. The impacts on yield are shown in Fig. 3, both mapped at the 0.5°×0.5° lat., long. resolution of TEM and aggregated to the EPPA regions for scenarios (see Figure title) with and without climate policy, ozone policy and ozone damage.

Global effects of these yield changes (Fig. 3) can be summarized as follows. Positive yield effects of environmental change lead to positive agricultural production effects, and vice versa. However, the production effects are far smaller than the yield effects. The global yield effects range from an increase of over 60 % (*Climate and GHGs only*) to a decline of nearly 40 % (*High pollution*), while the crop production effects are no larger than±8 %. This reflects relative inelastic demand for crops because of a relatively inelastic demand for food, the ability to substitute other inputs for land (adapt), and the ability to shift land into or out of crops. The livestock production results bear little relationship to the yield effects for pasture.
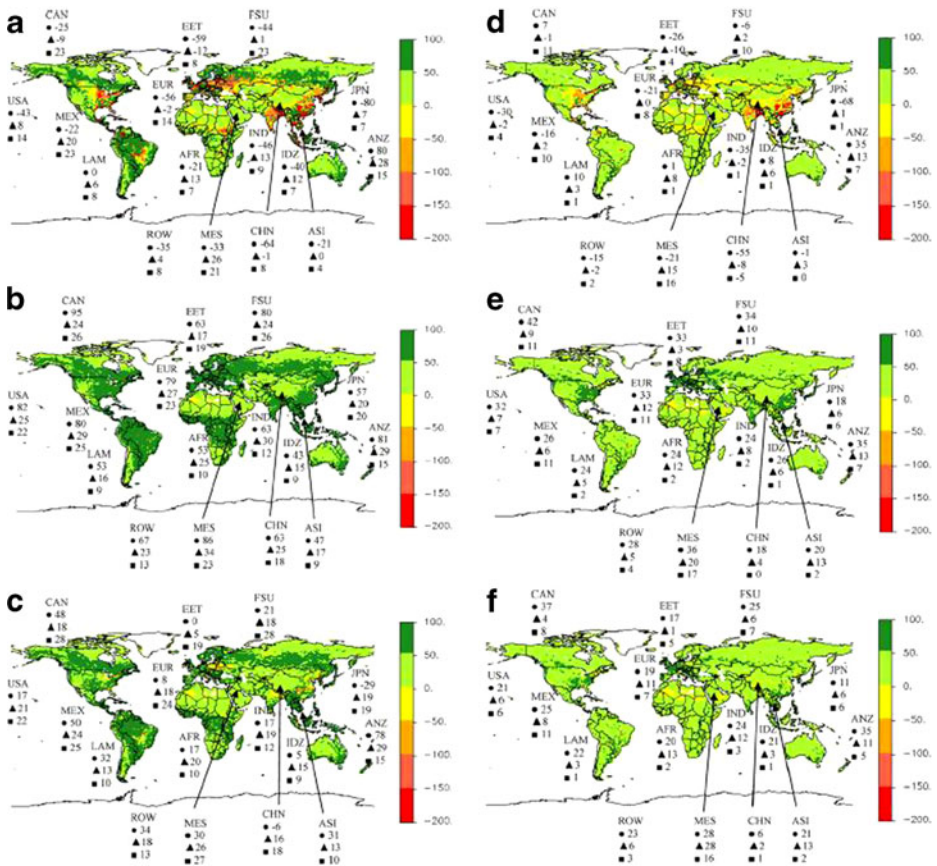

Fig. 3 Change in yield between 2000 and 2100 (gC/m2/year). Regional level percent changes in yield (crops) and NPP (pasture, forestry): *Black circle*—crops, *Black triangle*—pasture, *Black square*—forestry. **a** High Pollution scenario—no CO₂ or pollution controls. **b** Climate and GHGs only scenario—ozone damages removed **c** Capped pollution scenario—ozone precursors at 200o levels **d** GHGs capped scenario—consistent with 550 CO2-eq. stabilization **e** GHGs capped-no ozone scenario. **f** GHGs and pollution capped scenario. Source: Reilly, et al. 2007

The pasture results are all positive, whereas several of the scenarios show reductions in livestock production. In fact, the scenarios mirror closely the production effects on crops. This reflects the fact that feedgrains are more important inputs into livestock production than pasture. A reduction in crop production is reflected in higher prices for feedgrains and other crops used in livestock. This tends to lead to a reduced production of livestock. The percentage differences in livestock production are relatively small compared with the crop production changes, even in cases where production increases are driven both by an increase in crop production and an increase in pasture productivity.

An important result of the general equilibrium modeling of these impacts is that effects can be felt beyond the agricultural sector. The macroeconomic consumption effect was bigger in absolute terms than the agricultural production effect. This is because food consumption is relatively inelastic, and in order to offset the yield reduction more resources (i.e. labor, capital, intermediate inputs) are used in the agricultural sectors –and so, fewer are available elsewhere in the economy. Partial equilibrium approaches would not easily pick up all of these interactions – and so, may misestimate the impacts. For example, researchers often point to the tremendous adaptation response of agriculture. We see evidence of that in our results, but that adaptation also comes at a cost to the rest of the economy.

3.3 Challenges in valuing impacts on terrestrial and ocean ecosystems

Impacts on ecosystems offer some of the biggest challenges to valuation. Some ecosystem goods and services can be reflected in market goods and services. In one set of work, we have introduced data on hunting, fishing and wildlife viewing into the SAM underlying the EPPA model (Antoine, et al. 2008). Here the work was based on traditional travel cost methods that identified market goods used in conjunction with these recreation activities, as well as government expenditures on park and preserves maintenance. This creates some scarcity value on forest resources. And as income grows in the model, demand for both protected public- and privately-held forests for recreation increased. The increased demand for recreation services is a competitive pressure that limits conversion of these lands to cropland or other managed uses. Depending on parameter choices, the land conversion rates were similar to other work by Gurgel et al. (2007) that imposed an elasticity of "willingness to convert" that was benchmarked to observed conversion rates and land price changes. Adding an explicit consumer value to not converting offers a welfare-based reason for the limited conversion. Otherwise in the Gurgel et al. (2007) work, an ever-growing price wedge exists between natural lands and managed land types. Gurgel et al. (2011) extended ecosystem service pricing to include its carbon value in a mitigation scenario. Thus, potential losses or gains of carbon storage due to climate change are valued in terms of the impact on reaching the designated carbon limit or carbon price. Antoine et al. (2008) demonstrated that land conversion was strongly affected by choices for elasticities of substation among recreation goods and between recreation goods and other goods, and hence the value of recreation services. In almost all conventional ecosystem valuation exercises the per-unit-value of service is assumed to be constant, and there is no attempt to evaluate willingness to substitute other goods for the recreation goods. In principle, this method could be used to evaluate climate change impacts as it might affect the amount of forest or other natural land, but what is probably more critical and uncertain is to understand how climate change would affect the quality of forest resources for recreation purposes.

Valuing changes in oceans due to climate change also poses challenges. In principle, recreation values of coral reefs and food value of fisheries can be address in a fashion similar to how we have addressed agriculture and forest recreation services. However, climate effects on oceans will change in many ways. Habitats of marine species will shift with the

warming surface ocean (see e.g. Boyd and Doney 2002), and shifts in ocean circulation and mixing will reduce the supply of the nutrients to the surface ocean with ramifications to the base of the marine food web (e.g. Dutkiewicz et al. 2005). These will most certainly affect fisheries, but relating changes in nutrients to fish populations remains speculative. Additionally, reduced oxygen content of the ocean (a result of warming and lower mixing) will lead to more frequent anoxic (no oxygen) and hypoxic (low oxygen) events with fish and benthic organism (e.g. crab) kill-offs that will also impact the ocean's supply of food. While we have not yet related such changes to economic valuation, we have made progress in examining the first level of biological impacts in the IGSM framework (Dutkiewicz et al. 2005; Dutkiewicz et al 2012).

Yet another threat to the oceans is the increased acidity (lower pH) caused by the flux of anthropogenic carbon dioxide into the oceans. The oceans are currently absorbing about 1/3 of the emitted CO_2 (Sabine and Feely 2007), which has already led to a 0.1pH drop since pre-industrial times (Royal Society 2005) – a result that is captured in our simulations with the IGSM (Fig. 4). With the IGSM we can explore the potential pH drops in future scenarios (Prinn et al. 2011). Unprecedentedly low pH will occur even under strong policy-restricted emissions, but the picture will be much worse with a business-as-usual scenario. The reduction in pH will strongly affect the marine biota (Doney et al. 2009), with economic implications for fisheries (Cooley and Doney 2009). Calcifying organism (e.g. corals, molluscs) will be particularly vulnerable. Corals are likely to cease to exist with pH around 7.7 (likely in a no-policy scenario), but will change in type and diversity with even small changes (Fabricius et al. 2011). The impact on coral reef-driven tourism (a crucial component of the GDP for some nations) could be significant. But, these changes in the ocean acidity, temperature and circulation are so profound that we really do not know how they may affect life on earth as we know it. In that sense, focusing on a few market impacts – while important for some sectors and countries – may be missing the big picture and have far more threatening effects.
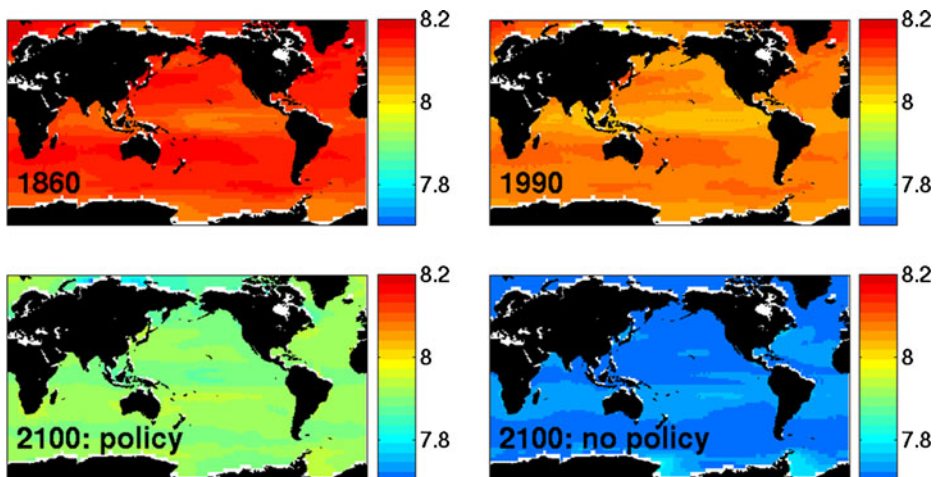

Fig. 4 Simulations of changes to the surface ocean pH (lower pH indicates a more acidic ocean) using the IGSM with a 3-dimensional ocean with biogeochemistry. Runs reflect business-as-usual (no policy) versus policy-restricted emissions scenarios, using a specified middle-of-the-road choice for climate sensitivity (approx. 2.3 K). The year 2100 atmospheric CO2 concentration for these two runs was 558 ppmv (policy) and 928 ppmv (no policy)

4 Uncertainties in future climate

Uncertainty is one of the key challenges for valuing impacts. Ideally, estimates of social cost of carbon should at a minimum reflect an expected value outcome. In general, however, the expected value of damage≠Damage (expected value climate outcome). If damages associated with mean climate outcomes are relatively mild, but the damages associated with extreme outcomes are catastrophic, then these catastrophic damages may dominate expected value calculations. In addition, an added weight on extreme outcomes may be required to reflect risk aversion and irreversibilities. To value these extremes requires robust climate models that can accurately describe details of the climate under extreme conditions and robust impact models that can address extreme conditions. Making progress toward valuing extreme outcomes and quantifying likelihoods of them occurring is a tall order. Our modest contribution has been to quantify that part of climate and economic uncertainty where there are known relationships and we can draw on estimates of uncertainty in underlying parameters of our IGSM to provide climate outcome likelihoods. Our estimates of quantifiable uncertainties (see Supplementary Material) used formal Monte Carlo simulation methods and estimated climate uncertainty conditional on different policy scenarios (Sokolov et al. 2009; Webster et al. 2012). A benefit of this approach is that we show the transient probabilities of climate change and, for adaptation studies, what happens in the next 10, 20 or at most 30 years is far more relevant than projects for 100 years.

5 Conclusions

Valuing impacts of climate change and reducing them to a single value, such as the social cost of carbon, is an extremely challenging task. In this paper we discuss our general strategy for investigating impacts of climate change; describe features of the MIT IGSM that allow us to estimate physical and biological changes caused by climate change; and briefly go through the needed steps to incorporate effects in a CGE model where valuation in equivalent variation is an output. We begin with the basic data that supports CGE models: the Social Accounting Matrix (SAM), which includes the input–output tables of an economy, the use and supply of factors, and the disposition of goods in final consumption. We identify where environmental damage appears in these accounts, estimate the physical loss, and value the loss within this accounting structure. Our approach is an exercise in environmental accounting – augmenting the standard national income and product accounts to include environmental damage. We are still some ways off from comprehensively estimating even those impacts that have been well-described (water and coasts, for example). And we have yet to utilize our capabilities for conducting uncertainty analysis to better understand the range of potential future impacts. We, like others in the field, face the problem that consequences that may have significant social cost may not be evident until we witness them.

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