OMITTED DAMAGES:

What's Missing From the Social Cost of Carbon

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ABSTRACT

The 2013 Interagency Working Group on the Social Cost of Carbon (IWG) updated the U.S. social cost of carbon (SCC) for 2015 from a central value of $24 to $37 using three integrated assessment models (IAMs): DICE-2010, FUND 3.8, and PAGE09. The SCC is the additional economic damage caused by one ton of carbon dioxide. While some have questioned the increase in the SCC as too high, a thorough examination of the latest scientific and economic research shows that $37 should be viewed as a lower bound. This is because the studies available to estimate the SCC omit many climate impacts—effectively valuing them at zero. Where estimates are available for a given type of impact, they tend to include only a portion of potential harms. This paper represents the first attempt to systematically examine and document these omissions for the latest versions of the three IAMs used by the IWG, as well as earlier versions when they are used in calibrating the updated models.

The table on the following page summarizes hot spot damages including increases in forced migration, social and political conflict, and violence; weather variability and extreme weather events; and declining growth rates. A better accounting of catastrophic damages is also needed, as well as many other impacts.

While there is a downward bias to the U.S. SCC estimates due to these omissions, the Office of Management and Budget (OMB) and other executive branch agencies should move forward to finalize proposed rules with the 2013 IWG's current SCC estimates, as measuring at least some of the costs of carbon dioxide is better than assuming they are zero. At the same time, the OMB should more thoroughly document downward biases of the current U.S. SCC estimates, potentially using this report to list in detail all of the currently omitted damages.

Missing or Poorly Quantified Damages Needed to Improve SCC Models*

General Impact	Category	Pages
Health	Respiratory illness from increased ozone pollution, pollen, and wildfire smoke	30
	Lyme disease	30
	Death, injuries, and illnesses from omitted natural disasters and mass migration	30
	Water, food, sanitation, and shelter	30
Agriculture	Weeds, pests and pathogens	20
	Food price spikes	Note 83
	Heat and precipitation extremes	41
Oceans	Acidification, temperature, and extreme weather impacts on fisheries, species extinction and migration, and coral reefs	18-20, 41-42
	Storm surge interaction with sea level rise	37-38
Forests	Ecosystem changes such as pest infestations and pathogens, species invasion and migration, flooding and soil erosion	20
	Wildfire, including acreage burned, public health impacts from smoke pollution, property losses, and fire management costs (including injuries and deaths)	20, 30
Ecosystems	Biodiversity**, habitat**, and species extinction**	29
	Outdoor recreation** and tourism	23
	Ecosystem services**	27-28
	Rising value of ecosystems due to increased scarcity	31-32
	Accelerated decline due to mass migration	34

General Impact	Category	Pages
Productivity and economic growth	Impacts on labor productivity and supply from extreme heat and weather, and multiple public health impacts across different damage categories	24-25
	Impacts on infrastructure and capital productivity and supply from damages from extreme weather events and infrastructure and diversion of financial resources toward climate adaptation	25
	Impact on research and development from diversion of financial resources toward climate adaptation	25
Water	Availability and competing needs for energy production, sanitation, and other uses	21, 41
	Flooding	41
Transportation	Changes in land and ocean transportation	21-22
Energy	Energy supply disruptions	21
Catastrophic impacts and tipping points**	Rapid sea level rise**	8, 36
	Methane releases from permafrost**	8, 36
	Damages at very high temperatures***	Note 23
	Unknown catastrophic events	36-37
Inter- and intra-regional conflict	National security	39, 41
	Increased violent conflicts from refugee migration from extreme weather, and food, water and land scarcity	34-35

*This table catalogues climate impacts that have been largely unquantified in the economics literature and are therefore largely omitted from SCC models. Quantified impacts represented in the models include: changes in energy (via cooling and heating) demand; changes in agricultural and forestry output from changes in average temperature and precipitation levels, and CO_2 fertilization; property lost to sea level rise; coastal storms; heat-related illnesses; and some diseases (e.g. malaria and dengue fever).

** These impacts are represented in a limited way in one or more of the SCC models: 1) they may be Included in some models, and not others; 2) they may be included only partially (e.g., only one or several impacts of many in the category are estimated); 3) they may be estimated using only general terms not specific to any one damage—in these instances, estimated damages are usually very small relative to their potential magnitude, and relative to the impacts explicitly estimated in the models. See complete report for details.

*** While technically represented in SCC models through extrapolations from small temperature changes, there are no available climate damage estimates for large temperature changes, and these may be catastrophic.

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Peter Howard*

In 2008, the United States Court of Appeals for the Ninth Circuit ruled that executive branch agencies must include the climate benefits of a significant regulatory action in federal benefit-cost analyses (BCA) to comply with Executive Order 12,866. In response, an Interagency Working Group on the Social Cost of Carbon was formed in 2010 to develop a consistent and defensible estimate of the social cost of carbon (SCC) using models drawn from the literature (Masur and Posner 2011). The SCC is the global cost to all future generations from one additional unit of carbon pollution in a given time period; forest fires, drought, and disease are just some of the costly consequences of climate change that are ideally included within it.[1] Thus, the SCC captures the benefit of reduced carbon pollution from a policy in terms of expenses avoided.

The SCC is estimated using Integrated Assessment Models (IAMs), which integrate a simplified climate model and a simplified economic model into a cohesive numerical model to capture the feedback effects between the two.[2] Using a methodology specified in the 2010 Technical Support Document (IWG, 2010), the 2010 Interagency Working Group developed a central estimate (corresponding to a constant discount rate of 3 percent) of $24 for a 2015 emission of carbon using three Integrated Assessment Models (IAMs): DICE-2007 (Nordhaus 2008), FUND 3.5 (Anthoff and Tol 2010), and PAGE2002 (Hope 2006). Using an identical methodology and updated versions of these three models—DICE-2010 (Nordhaus 2010), FUND 3.8 (Anthoff and Tol 2012),[3] and PAGE09 (Hope 2011)—the 2013 IWG re-estimated the central SCC estimate at $37 in 2015.[4] See Tables 1-3 for a full comparison of the 2010 and 2013 SCC estimates.

With its release by the 2013 Interagency Working Group on the Social Cost of Carbon (IWG), the U.S. government's updated social cost of carbon estimate catapulted into the national political debate. This surge in interest is mostly the result of the approximately 54 percent increase in the federal government's central 2015 SCC estimate from 2010 to 2013. Because the 2013 IWG used the same methodology to estimate the global SCC as the 2010 IWG (IWG 2013),[5] all changes in the SCC estimates are the result of updates to the three IAMs used for estimation. Regardless, considerable debate has ensued due to the significant implication this increase has on current and future U.S. policies.

While some conservative politicians and industry groups question the increase saying it is too high, this report shows more generally that, if anything, these SCC estimates are biased downward, probably significantly so. This downward bias is the result of modeling decisions by the 2010 IWG and modeling decisions by the authors of the current IAMS, including the use of outdated damage estimates and the omission of several climate

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change impacts. This report focuses primarily on omitted damages due to the likelihood that their inclusion would have a significant effect on the SCC.[6] These omissions include climate impacts on the following market sectors: agriculture, forestry, and fisheries (including pests, pathogens, and weeds, erosion, fires, and ocean acidification); ecosystem services (including biodiversity and habitat loss); health impacts (including Lyme disease and respiratory illness from increased ozone pollution, pollen, and wildfire smoke); inter-regional damages (including migration of human and economic capital); inter-sector damages (including the combined surge effects of stronger storms and rising sea levels), exacerbation of existing non-climate stresses (including the combined effect of the over pumping of groundwater and climate-driven reductions in regional water supplies); socially contingent damages (including increases in violence and other social conflict); decreasing growth rates (including decreases in labor productivity and increases in capital depreciation); weather variability (including increased drought and in-land flooding); and catastrophic impacts (including unknown unknowns on the scale of the rapid melting of Arctic permafrost or ice sheets).

Despite these downward biases to federal SCC estimates, this report argues that the Office of Management and Budget (OMB) and other executive branch agencies should move forward to finalize proposed rules with the 2013 IWG's current SCC estimates; they are underestimates, but we should, at a minimum, count the damages we can. At the same time, the OMB should emphasize more strongly the downward bias of the current SCC estimates and commit to addressing this bias in future updates of the estimates.

This report focuses on identifying the important categories of harm from climate change that are omitted from current IAMs. We first review the general categories of climate damages. Second, we describe how the latest versions of the three IAMs (DICE-2013, FUND 3.6, and PAGE09) are calibrated.[7] Third, we discuss a frequent cause of omitting damages: a lack of sound damage estimate(s) in the literature resulting from scientific and economic uncertainty in determining the magnitude of the effect. Fourth, using the previous two sections as a basis, we discuss the important categories of damages that are omitted. Fifth, we discuss the treatment of adaptation in these models, and whether omitted damages are likely to be incurred. Finally, we conclude with a discussion of the findings and what our results imply for the future estimation of climate damages.

DAMAGES

The rising temperatures and ecological shifts brought on by global climate change are expected to affect myriad aspects of natural ecosystems and human civilization. Though climate change may create benefits in some regions and sectors, the long-term effects of climate change are projected to be overwhelmingly negative. To help policymakers weigh the costs of climate mitigation and adaptation, these impacts are monetized by economists as damages. Damages can be broadly segmented into market damages, which manifest as a loss of gross domestic product (GDP) and non-market damages, which manifest in terms of lost welfare. Damages also include shocks to political stability, massive ecological regime changes (such as tipping points and mass species extinction), and impediments to sustained economic growth, none of which are easily predicted or quantified (U.S. Climate Change Science Program, 2008; Yohe and Tirpak 2008).

Market Damages

Market damages refer to changes in welfare due to changes in income or the availability, quality, or price of a market commodity or input. Most market damages result from shifts in productivity and a corresponding shift in output and GDP. Market damages can also be the result of the loss or depreciation of capital such as land or infrastructure (Goulder and Pizer 2006; Mendelsohn 2003).[8]

Sectors in which market damages from climate change are forecast include agriculture, due to increased temperatures, CO_2 fertilization, changing rainfall patterns, pests, and pathogens; energy demand, largely due to the increased cost of space cooling and the decreased cost of space heating associated with global temperature rise; energy supply, due to changing energy supply costs (such as increasing power plant cooling costs) and extreme weather energy supply interruptions; transportation and communication, due to delays and infrastructure losses from extreme weather events; forestry, due to shifting suitable habitat ranges, pests, pathogens, and fires; fisheries, due to higher water temperatures, invasive species, and ocean acidification; and water resources, due to increased evaporation rates and changing rainfall patterns. Market damages in the form of land, property, and infrastructure loss and degradation are also expected as a result of sea level rise and extreme weather events. While health damages have market (for example, labor availability and increased healthcare costs) and non-market (such as suffering and the value of human life) aspects, the market damages from health are relatively small compared the non-market damages because households place a high value on human life (Tol 2009; Jorgenson et al., 2004).[9]

In some of these market sectors, climate change is projected to create a net benefit in some countries for low-level temperature increases. For example, increased temperature will increase agricultural and forestry productivity in some regions and increased CO_2 concentrations can improve the nutritional value of soil (via the CO_2 fertilization effect). In some models, the benefits in some sectors are significant enough to result in initial net benefits to the globe from climate change. These sector benefits and the resulting global net benefits, however, are expected to be short-lived as temperatures continue to rise (Warren et al., 2006; Jorgenson et al., 2004). While Tol (2009) finds evidence of net global benefits from climate change up to a 2.2 degrees Celsius increase in temperature, this threshold differs between the three IAMs and even within variants of the same IAM.[10] Some IAMs, such as many of the more recent variants of DICE, find no such evidence of initial benefits.[11]

Non-market Damages

Non-market damages refer to damages affecting goods or services for which no established market exists, but which still provide value to humans. These non-market goods and services, also referred to as non-market commodities, can generally be thought of as environmental good and services (such as ecosystem services). Environmental goods can be divided into use values, including direct-use values (for example, the pharmaceutical value of biodiversity) and indirect use values (such as the values of ecosystem, recreational, and aesthetic services), and non-use value (including existence, bequest, option, and altruistic values). Another way to subdivide non-market damages is into tangible damages, which by definition can be valued, and intangible damages, which by definition are extremely difficult to value given current methods. While economists have established valuation techniques for tangible damages, the accuracy of these estimates vary by the type of good and service. For example, use values, particularly direct-use values, are more easily quantified than non-use values.[12]

Projected damages to non-market goods from climate change that are included in one or more IAM include the loss of species and habitat, increases in rates of human mortality and morbidity, and changes in amenity values (that is, the direct welfare change from a more or less hospitable climate) (Anthoff and Tol 2012; Warren et al., 2006; Smith et al., 2003). All tangible damages from climate change are not included in IAMs, such as the medical value of biodiversity. Intangible benefits, including larger societal implications of climate change, have yet to be meaningfully addressed or incorporated into IAMs (Yohe and Tirpak 2008).

Socially Contingent Damages

Socially contingent damages are damages that result from changes in social dynamics due to climate change. Warmer temperatures, sea level rise, and changing water availability can affect how societies function. For example, mass migration will become more likely as some regions become more inhospitable. Similarly, interpersonal violence and social and political conflict will rise with increased food, water, and resource scarcity. The values of social dynamics are, in most cases, intangible (that is, unmeasured) given current valuation methods; it is difficult to quantify the social effect, let alone value it. As a consequence, socially contingent damages from climate change are almost completely excluded from IAMs.

Catastrophic Impacts

One of the most concerning aspects of climate change is the potential for catastrophic damages. Catastrophic damages are characterized as low probability-high damage events. These damages come from

- tipping points (also known as discontinuities)—"an environmental threshold over which small changes in the environmental state can causes rapid, frequently irreversible changes in ecosystem characteristics" (EDF, NRDC, Policy Integrity, and UCS comments, 2013);
- fat tails—uncertainty in the underlying economic and environmental parameters in IAMs that result in underlying "fat-tailed" distributions, which are distributions (often right skewed) characterized by an extended and fat tail on the upper end of the distribution relative to the normal (bell curve) distribution; and
- black swan events—(that is, unknown unknowns) that refer to currently unknown tipping points or parameter distributions.

While tipping points, fat tails, and black swan events are distinct concepts, they are overlapping issues; this is discussed further below. Furthermore, while IAMs often categorize catastrophic damages as a distinct type of damage from the previous three, they should actually be thought of as damages to market goods, non-market goods and services, and society via cataclysmic climate events—often thought of in this case as rapid and/or extreme climate change.

Catastrophic impacts are often cited as a key reason for immediate action on climate change. Using PAGE09, Hope (2013) demonstrates that tipping point damages, the first of these three types of damages, alone can be as important as economic damages in determining the social cost of carbon.

TIPPING POINTS. As mentioned above, an ecological tipping point is broadly defined as a threshold beyond which a small change in conditions causes rapid, often irreversible changes in ecosystem characteristics. Tipping points are generally more common in intricate systems with many interacting parts, such that even small changes in the system can potentially have large impacts through a snowball effect.[13] A simple but illustrative example of an ecological tipping point is the effect of deforestation in tropical rainforests. The large trees in the rainforest depend upon nutrient-rich topsoil to thrive. That topsoil is held in place by the root network of the plants it supports and can take centuries to accumulate. The removal of trees accelerates the rate of

Crowning fire in spruce forest. Photo: Murphy Karen, U.S. Fish and Wildlife Service

topsoil erosion while topsoil erosion impedes tree survival rates. Deforestation, then, creates a chicken-and-egg conundrum as reforestation efforts are doomed by a lack of topsoil and topsoil cannot be sustained without an established root network (Brahic 2009).

Within the context of climate change, a tipping point generally refers to a temperature or CO_2 concentration threshold beyond which (even by small perturbations) the future state of Earth's climate system is significantly and irreversibly altered. In other words, a tipping point is an abrupt change in the climate system between stable climate states at the regional scale (at the subcontinental scale or higher) or global scale (Overpeck and Cole 2006). Beyond the temperature or CO_2 concentration threshold that causes this abrupt change, ecological changes would be irreversible on human time scales even if temperature could be returned to pre-threshold levels (Overpeck and Cole 2006; Lemoine and Traeger 2011).

A global tipping point would likely be driven by a series of region-specific or system-specific tipping points (that is, tipping elements), which, taken collectively, would dramatically reduce the Earth's natural capacity to withstand climate change. Lenton et al., (2008) identifies the following tipping elements:

- Arctic sea-ice (decreased areal extent),
- Greenland ice sheet (decreased ice volume),
- West Antarctic ice sheet (decreased ice volume),
- Atlantic thermohaline circulation (decreased overturning),
- El Niño-southern oscillation (increased amplitude),
- Indian summer monsoon (decreased rainfall),
- Sahara/Sahel and West African monsoon (increased vegetation fraction),
- Amazon rainforest (decreased tree fraction), and
- boreal forest (decreased tree fraction).[14]

The probability and damages of tipping point scenarios are poorly understood (Weitzman 2011). Due to the considerable uncertainty surrounding these events, some IAMs exclude them altogether. This will be discussed later.

Tipping point damages can be modeled either explicitly or implicitly. If tipping point damages are modeled explicitly, the damages from the crossing of tipping points are modeled using an additional damage function (for example, Hope 2002; Hope 2009; Nordhaus and Boyer 2000; Nordhaus 2008). If tipping point damages are implicitly modeled, tipping points are modeled in IAMs through the choice of climate parameters, specifically the probability distribution functions that represent them, as in Lemoine and Traeger (2011), Weitzman (2009), and Anthoff and Tol (2013a).[15] In this case, tipping point damages are implicitly captured through assumed increases in market and non-market damages resulting from higher temperature from crossing climate tipping point.

Fat Tails. Fat tails refer to the upper ends (that is, the right sides) of the probability density functions of a range of climate change-related variables. Tail fatness is an indicator of how quickly the probability of an event declines relative to the severity of that event, with fatter tails corresponding to lower rates of decline.[16]

Martin Weitzman has argued that existing climate models fail to adequately account for the extreme risks of climate change. In Weitzman's eyes, prevailing "structural uncertainties" (that is, unknown unknowns) abound in the economics of climate change, and existing benefit-cost analyses (BCAs) and IAMs have yet to deal adequately with these uncertainties. While IAM modelers often choose thin tailed distributions (for example, the uniform distribution) and medium-tailed distributions (for example, the normal distribution) to represent uncertain climate variables, Weitzman argues that fat-tailed distributions (for example, Student-t-distribution) are more appropriate due to these structural uncertainties in climate change (that is, unknown unknowns) and the "unlimited" potential for the scale of damages (Weitzman 2011).[17] Fat tails arise due to the finite amount of information on catastrophic impacts (due to their rarity in historical record keeping) forcing analysts to specify probability distribution functions of probability distribution functions. In other words, Weitzman believes that existing IAMs and BCAs under account for the potential of extreme, irreversible impacts of climate change by assuming thin-tailed and medium-tailed distribution functions,[18] which render the likelihood of extreme damages from climate change small enough to write off (Weitzman 2009; Nordhaus 2012).

Weitzman (2011) identifies multiple sources of structural uncertainty in existing climate modeling literature and models; he emphasizes that these sources are not exhaustive, and more likely exist. The five structural uncertainties that he identifies are: (1) the unprecedented rate and scope of increases in atmospheric greenhouse gas (GHG) concentrations, (2) the uncertainty surrounding the response of global temperatures to this dramatic increase in GHG emissions, (3) the potential for positive feedback mechanisms to accelerate the release of GHGs such as methane, (4) uncertainty of the effects (that is, damages) of extreme climate change,[19] and (5) the proper discounting of the distant future (Weitzman 2011). At each of these steps in the climate model, parameters are highly uncertain and potentially represented by fat tails. As a consequence of the "cascading" uncertainties at each step in the climate model and the potentiality of fat tails at each step, climate impacts are also likely fat tailed. As Weitzman (2011) emphasizes, this is the fat tail that truly matters to climate economics—not the fat tails of the climate sensitivity parameter and the other parameters—for the Dismal Theorem to arise.

As a result of the potential for climate impacts having a fat tail, Weitzman develops a theory now dubbed the Dismal Theorem. According to Weitzman (2009), if IAMs were to model fat-tailed distributions, the expected marginal utility of consumption would "explode." In other words, the "limiting [willingness to pay] to avoid fat-tailed disasters constitutes all of output (Weitzman, 2011)." As a consequence of this result, traditional BCA collapses as the SCC becomes infinite.

While Weitzman (2009) suggests such events can have such large costs as to overwhelm the discount rate, Nordhaus (2009) finds Weitzman's results are exceptions to the rule. In particular, Nordhaus (2009) find that the Dismal Theory holds, that is, the expected cost of climate change is infinite, only under limited conditions: the tails are "very" fat or society is "very" risk adverse. In other words, "[the probability of a catastrophic event] must not go to zero and [marginal utility of consumption] must be indefinitely large as consumption declines" towards zero (Nordhaus 2012); Nordhaus argues that the former condition may not hold (particularly if there is an upper bound on climate parameters), and the latter condition does not hold. Furthermore, using DICE-2007, Nordhaus (2009) demonstrates that catastrophic outcomes are potentially avoided, even if the climate sensitivity parameter is high and major tipping points exist, if policymakers can learn about the risks of climate change before irreversible, catastrophic damages occur and policymaking works correctly. However, Nordhaus' rebuff of the Dismal Theory (and its implication that BCA does not apply to climate change) should not be construed as a rejection of fat tails—these he believes are important for inclusion in IAMs (Nordhaus 2012).

In response, Weitzman (2011) argues that the infinite number should not become a distraction, but merely emphasize the larger willingness to pay to avoid these structural uncertainties discussed above. To produce a finite SCC for BCA to continue, Weitzman argues for the inclusion of the value of civilization. Like the value of a statistical life, the value of civilization captures the "rate of substitution between consumption and the mortality risk of a catastrophic extinction of civilization or the natural world as we know these concepts (Weitzman 2009)." Crudely calculated, the value of civilization equals the present value of global income in the year that civilization would end divided by the probability that civilization would end in that year (Weitzman 2009; Weitzman 2011).[20]

The empirical work on catastrophic damages, that is, the willingness to pay to avoid structural uncertainty, finds mixed results. On the one hand, Newbold and Daigneault (2009) find large catastrophe risk premiums. In this case, the use of the value of civilization may be essential. On the other hand, Pindyck (2009) finds only a modest risk premium. Similarly, Nordhaus (2009) only finds large catastrophic damages when climate policy fails in the presence of high climate sensitivity and major tipping points. In these cases, the inclusion of a value of civilization may be unnecessary because benefit-cost analysis does not collapse.

Note that there is some overlap between tipping point events and fat tails. If tipping point damages are modeled explicitly, the probability of incurring tipping point damages can be modeled using a fat-tailed distribution if the probability distribution function of the event occurring is unknown. Similarly, the corresponding magnitude of the damages can be modeled using fat-tailed distributions if this probability distribution function (PDF) is also uncertain. If tipping point damages are modeled implicitly, that is, climate parameters are used to model tipping points explicitly, fat-tailed distributions can be used for the corresponding climate parameters' probability distribution functions. However, tipping points do not require fat-tail distributions if they are known unknowns. In other words, the use of fat tails to model the probability of tipping points or their damages is not necessary to the extent that their probability distribution functions are known, and they can be captured by thin- or medium-tailed distributions. Undoubtedly, some tipping points are unknown unknowns and require the use of fat tails in that probability and damages of tipping point scenarios are poorly understood (Weitzman 2011).

BLACK SWAN EVENTS. Black swan events refer to unknown catastrophic impacts, via unknown tipping point events or parameters within unknown probability distribution functions. Currently, black swan events still go unaddressed by IAMs. Along with the view that omitted climate damages likely outweigh omitted climate benefits (Mastrandrea 2009), there exists a general opinion that bad surprises are likely to outweigh good surprises in the case of climate change (Tol 2009b; Mastrandrea 2009).[21]

Just as tipping points and fat tails are related concepts, so are fat tails and black swan events. Fat tails can be thought of as a general way to capture unknown unknowns in the SCC. However, the choice of fat-tailed distributions, that is, the rate that the tail declines, is unknown. In other words, specifying a fat-tailed distribution is guessing at unknown unknowns. Furthermore, in terms of real practical applications, IAMs that include fat tails may still omit other unknown unknowns. In this sense, the inclusion of fat-tailed distributions into IAM models may not fully capture unknown unknowns.

CALIBRATION

Through the choice of damage sectors and the choice of calibration estimates, IAM developers determine what damages from climate change are included and excluded in the social cost of carbon.[22] Using damage estimates (measured as a percentage change in GDP) for a specified temperature increase (measured as the degree Celsius increase in regional or global average temperate from the pre-industrial temperature) drawn from the literature,[23] IAM developers calibrate damage functions in three ways: sector-region analysis, survey, or meta-analysis.

First, a sector-regional analysis is when studies are found that provide sector-specific damage estimates by region; extrapolation from observed regional damages to missing regions is often necessary. If an aggregate damage function is utilized, damages are summed across sectors and regions. Earlier versions of DICE (DICE-1999 and DICE-2007) fall within this category, as does FUND.[24] Second, a survey of the literature is when a consensus work, like the IPCC studies, is utilized, or when the author uses his discretion to decide on the level of damages. In either case, though no statistical analysis is performed, the damage estimates are based upon a survey of particular studies. PAGE relies on this methodology combined with uncertainty analysis.[25] Third, a meta-analysis is when a damage curve is fit to various damage estimates that vary in damage magnitude and future temperature level. The most recent version of DICE relies on this method. The latter two methods are problematic in that they make it difficult to determine the actual source behind the damage function, and thus, to determine what particular climate damages are included and excluded from the model.

In the following section, we discuss how each IAM is calibrated by its developer using the default version of each of these models.[26] This is done to reflect the version of the model that each modeler provides to the public and documents most thoroughly. Furthermore, the IWG uses the default versions of these IAMs. In the case of DICE-2013, which has not been utilized by the IWG, the default version is utilized for purposes of consistency.

Calibration of the DICE damage function

Since 2000, William Nordhaus has released four versions of the DICE model: DICE-99, DICE-2007, DICE-2010, and DICE-2013. Of these four models, DICE-2010 is not considered a major update of the DICE model but rather an aggregation of the RICE-2010 model, a regionalized version of DICE. Across all versions of DICE, William Nordhaus calibrates an aggregated global damage function that is quadratic in temperature.[27] The sources used to calibrate the DICE-RICE damage functions have changed over the various versions of the model. For the quadratic damage functions of the initial models, that is, DICE-99, DICE-2007, and DICE-2010, Nordhaus used damage estimates by sector drawn from specific sources and studies. For the more recent version of the model, that is, DICE-2013, Nordhaus utilizes a meta-analysis approach.

EARLY VERSIONS OF DICE. The DICE-99 damage function was calibrated against region-sector damage estimates for a 2.5 degree and 6 degree Celsius increase in global mean surface temperature above the pre-industrial level.[28] The sectors in the DICE-1999 model are: agriculture; other vulnerable markets—forestry, fisheries, water transportation, hotels and other lodging places, outdoor recreation, and energy; coastal—sea level rise and storms; health—malaria, dengue fever, other tropical diseases, and pollution; non-market amenities—the allocation of time to leisure activities; settlements and ecosystems; and catastrophic impacts. Thus, the DICE-1999 model includes market, non-market, and catastrophic damages. See Table 4 for sources of damage estimates and Table 5 for DICE-1999 region-sector specific damage estimates.[29] See forthcoming Appendix A for a full discussion of the calibration of DICE-1999.

Instead of DICE-1999, the 2010 Interagency Working Group utilized DICE-2007 in the estimation of the U.S. Social Cost of Carbon, as documented in the 2010 Technical Support Document. There are no major changes from DICE-1999 to DICE-2007. In particular, as with DICE-1999, Nordhaus uses sector-based damage estimates to calibrate the aggregate DICE-2007 damage function. There is no change in the types of damages.[30] See forthcoming Appendix B.

The 2013 Interagency Working Group utilized DICE-2010 to estimate the U.S. Social Cost of Carbon, as documented in the 2013 Technical Support Document. The actual calibration method is almost identical to DICE-2007. The main difference is that for the 2010 version of the model, Nordhaus explicitly specifies the aggregate damage function as a quadratic function of both sea-level rise and temperature, instead of only temperature (Nordhaus, 2010; Nordhaus and Sztorc, 2013). See forthcoming Appendix C.

Given the similarities between DICE-1999, DICE-2007, and DICE-2010, this paper focuses on the omitted damages from DICE-1999. Of these three versions of DICE, DICE-1999 is chosen because it is used by Hope as one of the calibration sources of the PAGE09 damage function.

RECENT VERSION OF DICE. Nordhaus states that DICE-2013 is the first major update of the DICE model since the 2007 version. There are three major updates from 2007 to 2013 in the DICE aggregate damage function. First, Nordhaus updates the sources of his damage estimates used for calibration. Instead of using Nordhaus and Boyer (2000) as the basis of this calibration, he uses the damage estimates in Table 1 of Tol (2009), as seen in Table 7 below and Figure 2 in Nordhaus and Sztorc (2013). Second, he increases these damage estimates by 25 percent to account for omitted non-monetized benefits, such as "several important factors (biodiversity, ocean acidification, and political reactions), extreme events (sea-level rise, changes in ocean circulation, and accelerated climate change), impacts that are inherently difficult to model (catastrophic events and very long-term warming), and uncertainty (of virtually all components from economic growth to damages)." Last, Nordhaus no longer utilizes a sector-region analysis to calibrate DICE's aggregate damage function, but instead switches to the meta-analysis technique; see forthcoming Appendix D.

Determining what damages are included and excluded from the DICE-2013 damage function is difficult. This is because Nordhaus switches from a sector-region analysis to calibrate DICE's aggregate damage function to the meta-analysis technique, which relies on 13 studies cited in Tol (2009); see Table 7. For several reasons, this makes determining the damages included in the DICE-2013 model nearly impossible. First, many of the studies cited in Tol (2009) rely on a multitude of studies to produce their estimates, resulting in the need to go through a large number of papers in detail to decipher what damages are included and excluded from DICE. Second, when these studies do not rely on a multitude of cited papers, they utilize author discretion or statistical techniques to determine damage estimates. Both of these methods make it difficult to determine which sectors are included in the damage estimates, and the latter estimates, which include cross-national regressions, can often suffer from statistical inference problems. Last, it is difficult to determine what damages are included in the damage function because the 13 studies differ in what damages they include and exclude in their analyses. Specifically, what does it mean to have one of 13 studies include catastrophic damages or three out of 13 studies explicitly model the effect of climate change on vector-borne diseases? It seems reasonable to argue that the inclusion of these damages by a minority of studies implies their general exclusion from the DICE-2013 damage function. However, two studies exclude non-market damages and another two studies exclude market damages. Are non-market damages and market damages completely accounted for in DICE-2013? The answer to this question is debatable.

The DICE-2013 damage function was not used by either the 2010 or 2013 Interagency Working Group because the model was not yet peer-reviewed. It is our view that the IWG should be wary of using DICE-2013 in the future, given the inherent difficulty in understanding its foundations. Furthermore, if a meta-analysis is used, it should be conducted at either the sector or region-sector levels where more data are available. This is discussed further in the conclusion.

Calibration of the FUND 3.6 damage functions

FUND 3.6 is the only model of the three to model damages as functions of physical processes. Specifically, in FUND, Tol calibrates sector-specific damages functions to a 1 degree Celsius increase in temperature, and assumes dynamic equations to extrapolate damage estimates to higher temperature levels and different future states (rate of climate change, CO_2 levels, and socio-economic scenarios). These equations depend on various assumptions about physical and economic processes, and also rely on additional parameter calibration. Unlike DICE and PAGE, some sector damages, that is, agriculture and ecosystem services, are functions of the rate of temperature change, in addition to the level of temperature change, sea-level rise, and amount of CO_2 in the atmosphere.

FUND includes market and non-market damages, but fails to explicitly model catastrophic damages. The model's damage sectors include: agriculture, energy consumption, forestry, (fresh) water resources, sea level rise, human health, ecosystem degradation, and extreme weather (Anthoff and Tol, 2012). While FUND does not explicitly model catastrophic damages, FUND captures catastrophic damages via uncertain parameters.[31] Of the three IAMs utilized by the IWG, FUND 3.6 is the only one to model a socially contingent response to climate change: migration from sea level rise.

For FUND 3.6, Anthoff and Tol (2012) calibrate multiple damage functions per sector. Tol and Anthoff (2013) calibrate three agricultural damage functions using agricultural damage estimates derived using a general equilibrium approach; the three damage functions model the effect of rate of climate change (the cost of farmer mal-adaptation), level of climate change (effect of temperature level on crop production), and carbon dioxide fertilization on agricultural production (potential increases in agricultural production due to a rise in the atmospheric concentration of CO_2), respectively. In energy, Anthoff and Tol include the cost to the energy sector due to increased demand for space cooling and decreased demand for space heating from a rise in temperature. In forestry, Anthoff and Tol (2012) include the cost of climate change impacts on industrial wood manufactured products from changes in mean temperature and atmospheric concentrations of carbon dioxide relative to pre-industrial levels. In water resources, Anthoff and Tol (2012) include the effect of climate change on fresh water resource. For sea level rise, Tol accounts for losses of dry land and wetland, the coastal protection and migration costs. In health, Tol accounts for the mortality and morbidity costs of diarrhea, vector-borne diseases (malaria, schistosomiasis, and dengue fever), and heat and cold related illnesses (cardiovascular and respiratory disorders) due to a rise in temperature. With respect to ecosystems, Anthoff and Tol (2012) estimate a value for species loss. Finally, with respect to storms, Tol estimates the economic costs of the destruction and the value of life lost from tropical storms (hurricanes, typhoons) and extratropical storms (cyclones).

Due to the extensive use of data sources necessary to calibrate the physical processes, this section does not contain an extensive discussion of data; see forthcoming Appendix E.

Calibration in the PAGE-2009 damage functions[32]

PAGE09 models damage functions for four generalized impact sectors: market, sea-level rise, non-market, and non-linear (or tipping point) damages. Hope (2011a; 2011b; 2013) specifies a triangular distribution for each of the parameters in the damage function.

The non-catastrophic damage functions in PAGE09 (market, non-market, and sea-level rise) are calibrated using various versions of DICE and FUND. Thus, PAGE09 omits similar damages as do these two models. In PAGE09, Hope calibrates the distribution of economic (that is, market), non-economic (that is, non-market), and sea-level rise damages as a percentage of GDP for a 3 degree temperature increase (corresponding to a 0.5 meter sea-level rise) using a range of damage estimates from Warren et al (2006) and the IPCC 4th Assessment Report (IPCC, 2007). Warren et al (2006) discusses DICE-1999, FUND2.9, PAGE02, and MERGE; PAGE2002 is calibrated based on DICE-1999 and FUND 2.0.[33] Fig 20.3a from AR4 WGII on page 822 (Figure 1 below), which is used to inform the range (the minimum and maximum combined effect) of market and non-market damages (a range between 0.3 percent to 1.8 percent GDP decline for a 2.5 degree Celsius increase), cites Nordhaus and Boyer (2000) – DICE-1999, Tol (2002b) – FUND 2.0, and Mendelsohn et al (2000); this figure is identical to Figure 19.4 in IPCC (2001a, Chapter 19) upon which the PAGE2002 damage estimates were partially based. In other words, the market, non-market, and sea-level damage functions in the PAGE09 model are “highly” dependent on DICE and FUND, though Hope uses his discretion to specify a range of estimates to allow for the possibility that these models have underestimated impacts.

Flooding in downtown Binghamton, New York due to the remnants of Tropical Storm Lee. Photo: National Weather Service, Binghamton

Hope (2011) also reduces the magnitude of these damages by including initial climate benefits, which can result in some regions experiencing positive net benefits from climate change at low temperature increases, and by placing a limit on climate damages so that they can be no greater than 100 percent of GDP at high temperature increases. In addition to damages, Hope (2011b) includes an additional terms in each of the three non-catastrophic impact sectors based on the findings of Tol (2002) to capture initial climate benefits for lower temperature increases; these initial benefits are set equal to zero for sea-level rise in the default version of the PAGE09 model.[34] These expressions are defined such that these benefits dissipate as temperature increase until they become zero (that is, do not yield any actual benefits) at some temperature threshold, and then they become damages (in addition to the previously discussed calibrated damages) for further temperature increases. Assuming no adaptation, the temperature thresholds for both market and non-market damages are 3 degrees Celsius.[35] Hope (2011) also limits damages to 100 percent of GDP in any given time period. Instead of maintaining polynomial damage functions across all temperature levels, damage functions shift from polynomial functions to logistic functions at certain damage levels to constrain damage to 100 percent of GDP. Following Weitzman (2009), the saturation point (that is, the point where damages as a percentage of consumption starts to become limited) is characterized by a triangular distribution with range 20 percent to 50 percent, a mean of 33.33 percent, and a mode of 30 percent (Hope, 2011a; 2011b). Given the modeling assumption of PAGE09, the initial benefit terms do not yield any actual benefits (that is, are equal to zero) and the damage functions are still polynomial functions for a 3 degree Celsius increase and a 0.5 meter sea-level rise. In other words, non-catastrophic damages equal their calibration value of 2.03 percent of GDP at the calibration temperatures increase of 3 degrees Celsius when there is no adaptation (Hope 2011).

In PAGE09, Hope explicitly models climate tipping points as a singular, discrete event that has a probability of occurring in each time period. This probability increases in temperature. If this event occurs, a decline of 5 percent to 25 percent of GDP occurs; See Table 9 below.[36]

PAGE09 calculates climate damages for the European Union, and then scales these damages to other regions. PAGE09 uses the relative length of coastline to inform the corresponding ranges of scaling factors; Anthoff et al., (2006) is the data source for the weighting factors. While these scaling factors do no differentiate between developed and developing countries, Hope includes equity weights in PAGE09 that account for differences in GDP per capita between European Union and other regions (Hope 2011b). Finally, Hope specifies regional damage functions in PAGE09, which are functions of regional temperature, not global mean surface temperature. Thus, PAGE09 captures some regional differences in climate damages using several mechanisms. See forthcoming Appendix F for further discussion.

Damages generally included in IAMs

From this discussion about how the three latest IAMs are calibrated, we can make some general statements about what types of damages are accounted for by IAMs. Currently, they cover a number of direct effects of climate change, that is, a rise in global average surface temperature, on economic (that is, market) activity, and to a lesser extent the direct effects of climate change on the environment and human settlements. The three Integrated Assessment Models (IAMs) capture the direct effects of higher temperature levels and higher CO_2 levels (via soil fertility) on agriculture and forestry yields (but excluding climate change effects on pests, pathogens, and fires), and the effects of trade through general equilibrium effects. The models only capture the effects of higher temperature on fisheries to a very limited extent, and exclude the effects of habitat loss (particularly mangroves and coral reefs), ocean acidification, and invasive species all together. The models also capture some effects of climate change on energy demand and fresh water resources, though these are still limited in important ways (see discussions on fisheries, energy supply, ecosystem services, and destabilizers of existing non-climate stressors below). While IAMs capture the effects of heat and cold related illnesses (cardiovascular and respiratory disorders) to different extents, all three capture some effects of climate on vector-borne diseases, including malaria and dengue fever. For example, the direct cost of vector-borne diseases on human life is included, but not the effects of such diseases on labor supply or productivity (as discussed below). To different extents, all three models capture the effects of increased storm strength on coastal property values and sea level rise on preventative expenditures, lost property, and lost ecosystems. To the extent possible with current models, all IAMs consider some effect of climate change on ecosystems and biodiversity—though improved estimates are needed with respect to both of these damage estimates. Finally, there are a variety of damages that are captured by only one or two of the IAMs, but not all three: effects of climate change on morbidity; mortality from storms, pollution, and diarrhea; recreational activities; climate amenities (that is, the willingness to pay to live in a location with more sunny days); and catastrophic damages.

As is discussed more thoroughly in the conclusion of this report, many of the smaller climate damages are not considered by the authors of IAMs because they are considered cancelled out by omitted climate benefits. The views of Tol (2009) and Yohe and Tirpak (2007) are that a better job has to be done with respect to including only major damage categories: catastrophic damages, socially contingent damages, and weather variability. See the conclusion of this paper for more of a discussion.

CAUSES OF THE OMISSION OF DAMAGES

In general, the more difficult a climate impact is to estimate in the natural sciences (which measure the physical impact) and/or value in economics, the more likely that climate impact is to be excluded from IAMs (Yohe and Tirpak, 2008); see Figure 2. With respect to the natural sciences, damages corresponding to more certain (that is, known) climate trends (for example, average temperature increases and sea level rise) are included in IAMs; bounded trends, that is, climate change for which a range and/or distribution is specified, such as extreme weather events and weather variability (for example, droughts, floods, storms, and so on), are less likely to be included; and abrupt changes, in general, are the least likely to be included because they are the effects characterized by the greatest uncertainty. With respect to economics, damages that are easier to value are more likely to be included, such that many more market damages are included than non-market damages. Environmental goods and services are more likely to be omitted from IAMs by analysts than market damages because the former does not have observable market prices and instead must be valued by the analysts. While the value of some environmental goods and services can be indirectly observed in market data (for example, housing sales) using revealed preference techniques, other environmental goods and services (for example, biodiversity) can only be valued using stated preference techniques;[37] this latter group of environmental goods and services are more likely to be omitted. Socially contingent damages (for example, famine, political unrest, migration, and so on), which are often the result of multiple stressors, are usually omitted because they are difficult to quantify, predict, and value (Yohe and Tirpak, 2008). Figure 2 below, taken from Yohe and Tirpak (2008), organizes all types of climate damages into nine categories of damages corresponding to three levels of scientific uncertainty (that is, three rows) and three levels of economics uncertainty (that is, three columns) discussed above.

The nine categories of climate of climate benefits and damages in Figure 2 (and discussed in the previous paragraph) can be further organized into three groups of damages based on their levels of representation in IAMs:

- Group 1: Included damages—market damages from certain climate trends. Area I in Figure 2.
- Group 2: Partially included damages—bounded and tipping-point market damages and certain and bounded non-market damages. Areas II, III, IV, and V in Figure 2.
- Group 3: Excluded damages—socially-contingent damages and non-market tipping point damages. Areas VI, VII, VIII, and IX in Figure 2.

Group 1 damages, that is, certain market damages, are included, but can still be improved by accounting for geographic variability. Other market damages, for all real purposes, are excluded: fisheries, energy supply, transportation, communication, and recreation and tourism.

Group 2, which includes bounded and tipping-point market damages and certain and bounded non-market damages, has been less successfully included into IAMs. The three IAMs have included certain and bounded non-market damages, but in a less than comprehensive manner due to data and method limitations. In other words, while many of these damages have been included in IAMS (for example, heat stress, loss of wetlands, biodiversity, and loss of life), the included estimates require significant improvement.[38] Similarly, while some IAMs (earlier versions of DICE and PAGE), have explicitly accounted for catastrophic market damages, Yohe and Tirpak (2008) argue that these estimates have been less than comprehensive, and most likely omit non-market and socially contingent consequences of these changes.[39] Furthermore, while IAMs have included market sectors that are affected by climate variability (agriculture, fresh water resources, forestry), little has been done to account for the damages of increased climate variability in these sectors. It is critical to account for increased climate variability because average changes mask extreme events, such as droughts, heavy rains, heat waves, and cold spells.

Group 3, that is, socially contingent damages and non-market tipping point damages, has only recently been investigated (or has not been investigated at all) by impact papers. As a consequence, they are completely omitted from IAMs (Yohe and Tirpak, 2008).

With each generation of IAM, a discussion ensues over whether climate damages are accurately captured. While several studies have identified missing damages in earlier versions of these three IAMs (Warren et al., 2006; Dietz et al., 2007; Yohe and Tirpak, 2008; Tol, 2009), this report is the first to thoroughly identify and discuss the various damages omitted from the most recent versions of these three IAMs (specially the default versions): DICE-2013, FUND 3.6 (which is identical to FUND 3.7 and FUND 3.8 in terms of damage captured), and PAGE09. By analyzing the calibration methods and data sources of the latest version of the three IAMs, as discussed in the previous section, this report is able to provide a comprehensive discussion of which important categories of harm are included and excluded from these IAMs. Please see Appendices A through F for a more thorough discussion of the calibration of each IAM, and which damages are included and excluded from the default version of each of these models.

OMITTED DAMAGES

Based on the analysis of the three IAMs in the previous two sections, this section will discuss the damages currently omitted from IAMs: market damages—fisheries, pests (IWG, 2010), pathogens (IWG 2010), erosion (Vose et al., 2012), weeds (Rosenzweig et al., 2001), air pollution (Warren et al., 2006; Cline, 1992), fire (Cline, 1992), energy supply (Tol, 2009; IPCC, 2007b), transportation (IPCC, 2007b; Koetse and Rietveld, 2009), communication, ecological dynamics (Gitay et al., 2001; Norby et al., 2005), and decreasing growth rate (Fankhauser and Tol, 2005; Tol, 2009; Dell, Jones, and Olken, 2013; Moyer et al., 2013); non-market damages—recreational value (Tol, 2009), ecosystem services, biodiversity and habitat (IWG 2010; Tol, 2009; Nordhaus and Sztorc, 2013; Freeman and Guzman, 2009), omitted health costs (Tol, 2002a; Warren et al., 2006), and relative prices (IWG, 2010; Sterner and Persson, 2008; Hoel and Sterner, 2007); socially contingent damages— migration, social and political conflict, and violence (Stern, 2007–Chapter 6; Yohe and Tirpak, 2008; Tol, 2009; Dell, Jones, and Olken, 2013); catastrophic impacts (IWG 2010; Yohe and Tirpak, 2008; Tol, 2009); inter-regional damages (IWG 2010); and across sector damages—inter-sector damages (IWG, 2010; Warren et al., 2006), exacerbation of existing non-climate stresses (Free man and Guzman, 2009), ocean acidification (Brander et al., 2009; Cooley and Doney, 2009; Guinotte and Fabry, 2009), and weather variability (Yohe and Tirpak, 2008; IWG, 2010).[40]

Omitted damages can involve omitted damage sectors, such as fisheries, or omitted effects of climate change within and across sectors, such as ocean acidification. This poses a taxonomy problem in that it is hard to classify damages within the simple market, non-market, socially contingent, and catastrophic damage categories that we have laid out earlier. For clarification purposes, we highlight when this is a particular problem with respect to omitted effects of climate change: ocean acidification; wildfires; and pests, pathogens, and weeds.[41] In addition, we add two additional types of omitted damages to the taxonomy: inter-sector damages and cross-sector damages. The former captures the damages that arise due to the interaction of climate change effects between two or more damage sectors, and the latter captures omitted damages that affect multiple sectors. See Table 10 for the taxonomy of omitted damages used in this paper, and Table 11 for an alternative taxonomy based on omitted damage sectors and omitted climate effects.

Market damages

There exist several market damages that remain unaccounted for in the market damage literature. As mentioned earlier, Yohe and Hope (2013) argue that few updates to market damages will have a significant effect. However, there are several potential additions that should be considered for having potentially large effects: fisheries (and relatedly, including effects of ocean acidification more broadly), market sector disturbances (pests, pathogens, air pollution, erosion, and fires), energy supply, transportation, and economic growth.

FISHERIES. Fisheries are, for the most part, excluded from IAMs. DICE-1999, which is utilized as a damage source in DICE-2010 and PAGE09 (both are used by the 2013 IWG), includes fisheries in a generalized "other market" sector, along with forestry, energy systems, water systems, construction, and outdoor recreation. Citing Cline (1992), Nordhaus (1991), and Mendelsohn and Neumann (1999) damages estimates to these sectors for the United States, Nordhaus and Boyer (2000) argue that damages not related to energy are equal to zero. Implicitly, this assumes that climate damages to fisheries are equal to zero even though the sources he cites do not explicitly discuss damages to fisheries, particularly Cline (1992) and Nordhaus (1991). As a consequence, Nordhaus and Boyer (2000) essentially fail to account for fisheries. In FUND 3.6, freshwater and saltwater fisheries are excluded. Consequently, PAGE09, which heavily relies on early versions of DICE and FUND to calibrate its market damage function, excludes fisheries as well. Finally, DICE-2013, at most, partially captures fisheries. Many of the enumerative studies upon which DICE-2013 relies in the calibration of its damage function, exclude fisheries altogether.[42] Similarly, in the statistical studies, the effect on fisheries, particularly offshore salt-water fisheries, may be excluded; see forthcoming Appendix D.[43]

Fisheries support a significant portion of the world's population. Many individuals rely on fishing and aquaculture for employment. Also, many individuals rely on seafood as their primary source of protein. Climate damages to fishery resources will cause particular harm to those regions most reliant on fisheries (WFC, 2007). According to Allison et al., (2009), the most vulnerable fisheries are located in developing nations, which are the most dependent on fisheries in terms of livelihood and nutrition.

Climate change will affect fisheries in several ways. First, rising sea surface temperatures will damage coral reefs, an important habitat for many fisheries, and result in more frequent algae blooms, which negatively affect fish stocks via decreased oxygen availability. Rising temperatures will also positively affect the growing season, winter mortality rates, and growth rates. Second, rising land temperatures will increase the temperatures of fresh water systems, resulting in declined fish stocks through reduced water quality, invasive species and pathogens, and decreased food abundance; again, warmer temperatures in cold waters may have some benefits in terms of increased growth rates. Third, rising sea levels will negatively affect coastal habitats, including mangroves and salt water marshes, and freshwater water habitats via saltwater intrusion; rising sea levels may also benefit shrimp and crab aquaculture. Fourth, increased weather variability and extreme events, including floods and droughts, and decreased water availability in some regions is likely to negatively affect fish stocks, particular fresh water and aquaculture; changing precipitation patterns may affect marine populations via water salinity (WFC 2007). Fifth, changes in ocean chemistry, including ocean acidification, which is discussed more below, and decreased oxygen content from increased algae blooms, which is discussed above, will negatively affect fish stocks, particularly mollusks. Sixth, melting sea ice may increase access to Arctic fisheries. Last, climate change will likely compound the negative effect that human activity, including over fishing, has on future fish stocks.[44] These damages and benefits will vary regionally, particularly as fish shift locations. They are also highly uncertain due to uncertainty over climate change and its effects (particularly on the scale that is relevant to marine life and fisheries – continental shelves), complex aquatic food web and ecosystem dynamics, the ability of species to adapt, and the range of human and environmental impacts fisheries (WFC, 2007; Hollowed et al., 2013; Sumaila et al., 2011).

Adaptation by species and humans may be able to reduce these negative effects. Fish species will be able to adapt to some of these change by moving toward the Poles and into deeper water (Sumaila et al., 2011). However, these changes may still result in habitat loss for some freshwater and saltwater fish, even with this ability to adapt, such that some species will experience declines and extinction (Hollowed et al., 2013). Furthermore, these shifts imply regional effects, such that some regions benefit and others are harmed (Hollowed et al., 2013), and quality effects, as fisherman are forced to switch to new species. Finally, humans may be able to adapt to mitigate losses and meet increased demand by expanding aquaculture to replace decreased wild catch and increasing trade (Brander 2010). However, human adaptation at the local level will come at an increased capital cost, and a loss of capital as some fisherman scrap their vessels (Sumaila et al., 2011).

In addition to climate change affecting fish stocks, climate change will also affect human capital and infrastructure necessary for production. Increased storm strength and frequency will negatively affect infrastructure, particularly aquaculture, located near coastal areas. Coupled with rising sea levels that will negatively affect coastal ecosystems that act as a buffer from coastal storms, storm effects could be significant (WFC, 2007). The ability of regions to adapt to these events will vary regionally.

There is a lack of estimates for the impacts of climate change on fisheries (Sumaila et al., 2011). This is partially due to the difficulty of estimating the net impacts on production across multiple species and uncertain future environments, which results in highly uncertain estimates. While it is clear that damages will vary regionally—hurting tropical regions and possibly benefiting artic regions—these regional results are uncertain given the large scale effects of climate change on oceans; this includes ocean acidification and higher ocean temperatures—both of which effect phytoplankton (Toseland et al., 2013).[45] Because developing nations are focused predominately in tropical and subtropical subclimates, fishing industries in poor nations are likely to be disproportionately affected. These nations are often already at an open-access equilibria due to overfishing and lack of management, and, as a consequence, are unlikely to experience a significant change in profits due to climate change. However, in developing nations, large portions of the population rely on subsistence fishing for calories and protein. Thus, the effects of climate change on consumer welfare via fisheries are likely to be substantial in developing nations.

NATURAL DISTURBANCES: PESTS, PATHOGENS, AND WEEDS, EROSION, AIR POLLUTION, AND FIRES. Pest (weeds and insects) and pathogens (Rosenzweig et al., 2001), erosion (Vose et al., 2012), air pollution (for example, the effects of climate change on increased ozone pollution, which affects crops and public health),[46,47] and fire are natural disturbances that affect agriculture and forestry. While these disturbances are currently being excluded from the agricultural and forestry sectors (Ackerman and Stanton, 2011, Cline 1992), these disturbances are likely to be substantially affected by climate change (IPCC, 2007b, Chapter 5). Climate may expand the geographical extent of pests, pathogens, and weeds (particularly for livestock and forests) and increase the likelihood and severity of pest and pathogen outbreaks due to earlier springs and more extreme events. Forestry may be negatively affected by increased erosion from higher precipitation and other extreme weather events (Vose et al., 2012). Increased ozone exposure will also decrease timber production and crop yields, while increasing crop susceptibility to pest outbreaks. Increased fire risks may decrease forestry production and costs (IPCC, 2007b), and have significant impacts on human health and infrastructure (Fowler, 2003). While each of these natural disturbances may have only modest effects, their interactions (along with drought) and their combined effects are likely to be substantial.

These natural disturbances also affect agricultural and forestry via the fertilization effect, which is the increase in plant growth, and thus production, from an increase of carbon dioxide in the atmosphere. Current estimates of the CO_2 fertilization effect are from laboratory experiments where plants are not subject to competition from pests, pathogens, and weeds that may also benefit from CO_2 fertilization.[48] More recent estimates, known as Free-Air CO_2 Enrichment (FACE) experiments, are field experiments where plants are subject to these pressures; the resulting benefits from increased CO_2 are lower under FACE experiments (Hanemann, 2008, IPCC, 2007a). Furthermore, air pollution (ozone), which is completely unaccounted for, may further limit the CO_2 fertilization effect (IPCC, 2007b Chapter 5).

Increased pests, pathogens, and weeds, erosion, air pollution, and fires will also affect ecosystems, wildlife, and human settlements. These costs are also currently excluded from the default versions of these IAMs.

ECOLOGICAL DYNAMICS. Ecological dynamics are omitted from the analysis despite their significance in timber production. In addition to disease and insects (Gitay et al., 2001; Norby et al., 2005) and wildfires, studies of climate change impacts on ecological dynamics of forests cited by Gitay et al., (2001) include those concerning, seasonality, timing of freeze-thaw patterns, length of growing season, nutrient feedbacks, disturbance, diurnal temperature patterns, local climatic extremes, late and early frost, changes in precipitation, and extreme weather events. Climate change will further affect forestry to the extent that these dynamics contribute to forest ecology and will be impacted by climate change.

ENERGY SUPPLY. Tol (2009) argues that energy costs may decrease due to climate change relative to a future world without climate change. This is due to decreased costs of supplying renewable energy from wind and wave sources, and the increased availability of oil due to higher temperatures in the Arctic. However, warmer water temperatures will increase the cooling costs of thermal power plants (conventional and nuclear), and decreased water availability in some regions may increase the cost of hydro-electric energy (IPCC, 2007b Chapter 1 and Chapter 7). The increased frequency and intensity of extreme weather events (heat waves, droughts, and storms) have the potential to further disrupt energy supplies, particularly coastal energy and energy transmission infrastructures, while the melting of permafrost is also threatening energy infrastructure in Arctic regions (IPCC, 2007 Chapter 7). It is difficult to determine whether the net effects of climate change on the cost of supply energy will be positive or negative.

TRANSPORTATION. Transportation is critical for the movement of populations and goods, including energy resources. However, the effects of climate change on the transportation sector in terms of lost infrastructure, costs, delays, and safety (including fatalities) are rarely emphasized according to Koetse and Rietveld (2009). This may partially be due to the sparse literature in this area and the general ambiguous effects of climate change on transportation due to countervailing effects (Koetse and Rietveld, 2009).

On the one hand, higher temperatures imply fewer transportation delays from snow and ice (Tol 2009, IPCC 2007). While traffic congestion and accidents result from adverse weather conditions (including rain, snow, and poor visibility), less snow overall will result in less traffic congestion and fewer accidents. Furthermore, many areas will experience decreased costs of dealing with these cold weather events, including less salting of roads and plowing equipment. While higher temperatures will also come with some costs, including buckled rails and roads, these costs can likely be overcome gradually with updating of the road and railway systems during their regular maintenance schedule. Higher temperatures also decrease ice cover in rivers, lakes, and oceans, which decreases shipping costs during the winter. In particular, higher Arctic temperatures may make shipping through the Northwest Passage possible at some times during the year; this has the potential to lower overall shipping costs (Koetse and Rietveld, 2009; IPCC, 2007).[49]

The BLM and the U.S. Forest Service work together to manage wildfires. Photo: Bureau of Land Management

On the other hand, greater weather variability and a higher frequency of extreme weather events (droughts, heavy precipitation events, floods, high winds, and storms) will potentially hurt traffic and disrupt transportation. While higher temperatures and less snow decrease some effects of climate change on traffic congestion, delays, and accidents, the overall effects are unclear because increased precipitation variability due to climate change will likely have a countervailing effect, as precipitation following a dry spell significantly increases the number of accidents (Koetse and Rietveld, 2009). Similarly, while decreased ice cover due to higher temperatures reduces shipping costs, extreme weather events significantly disrupt transportation and destroy transportation infrastructure. Flooding is particularly problematic for the transportation systems of coastal communities (and potentially the most costly of the transportation effects), while droughts will be more of a concern for inland waterway transportation.[50] In addition to the inconvenience to travelers, these events could disrupt trade due to the temporarily shutting down of trade routes, road and port closings, and train and airport delays and cancellations. While ports are more affected (in terms of area and numbers effected) by flooding and storm surges than roads, railways, and airports, even small effects to these latter three infrastructures may have significant costs due to network effects.[51] Due to the increase in exposure to extreme weather events, particularly along the coasts, without adaption, the costs from transportation delays and infrastructure losses will undoubtedly be substantial. Furthermore, changing weather patterns may change trade patterns, which may require infrastructure investment, and require that Arctic regions update their transportation infrastructure in response to melting permafrost (Koetse and Rietveld, 2009; IPCC, 2007).

Traffic safety in terms of the frequency of accidents and changes in mortality and injury rates due to accidents is also another important component of transportation costs. While adverse weather increases the likelihood of aircraft accidents, the bulk of deaths related to travel are road traffic related. However, calculating the change in related deaths due to climate change turns out to be complicated because of the complex number of effects: (1) higher temperatures increase the number of accidents due to heat-stress, (2) increased precipitation increases the frequency of accidents, (3) adverse weather decreases the severity of damages due to reduced traffic speed, (4) snowfall causes more accidents than rainfall, and (5) precipitation after a dry spell has a greater effect on accidents and fatal accidents than precipitation alone. Therefore, the effects of climate change on traffic mortalities and injuries are ambiguous, as is the case for traffic safety in general, congestion, and shipping costs. Effects will likely vary regionally (Koetse and Rietveld, 2009).

Adaptation is also likely to reduce some of the costs associated with extreme weather events. In particular, damages due to sea level rise and floods may be preventable through adaptation, including the building of sea walls. As a consequence, many of the current cost estimates available in the literature, which mainly focus on the eastern United States, may be upper bounds.

Current IAMs do not explicitly model climate damages to the transportation sector. DICE-1999 explicitly assumes transportation is negligibly effected by climate change (with the exception of water transportation), though it is possible in early versions of DICE that transportation costs may be captured indirectly through damages to human settlements and sea level rise. Similar to DICE, FUND does not explicitly address transportation costs, though climate damages due to storms and sea level rise may already include some of these costs. Because the market and sea level rise damages in PAGE09 are greatly informed by DICE and FUND, it is unclear the extent to which PAGE09 includes transportation costs. Similar issues arise for DICE-2013.

COMMUNICATION. Communication infrastructure will experience similar disruptions as the energy and transportation infrastructures due to extreme weather. While a possible adaptation is to bury these infrastructures underground, this strategy is costly (IPCC, 2007). Like energy and transportation, these costs are excluded from IAMs. However, Nordhaus and Boyer (2000) categorize damages to the communication sector as insignificant.

RECREATION. The recreation sector will also be affected by climate change, and is omitted from IAMs according to Tol (2009). While there are clearly redistribution effects across regions, its ultimate effect is uncertain according to Tol (2009). Similarly, Bigano et al (2007) find that climate change has unclear, but generally negligible, effects on global tourist expenditures.[52] Alternatively, using a general equilibrium model, Berrittella et al., (2006) find that "climate change will ultimately lead to a non-negligible global loss" in 2050. This estimate includes only the direct impacts of climate change on recreation, and it omits the indirect impacts such as the loss of some beaches and islands due to sea level rise and the loss of particular ecosystems (such as coral reefs) and species (such as polar bears). The inclusion of these indirect impacts will likely further increase the recreational cost of climate change.

CHANGES IN OUTPUT GROWTH. There is evidence that higher temperatures effect labor productivity (Kjellstrom et al., 2009), the growth rate of economic output (Dell, Jones, and Olken, 2009; Dell, Jones, and Olken, 2012; Hsiang, 2010), and the growth rate of exports (Jones and Olken, 2010), and some of these negative effects on growth continue into the medium-run and long-run (Dell, Jones, and Olken, 2009; Dell, Jones, and Olken, 2012). However, as discussed earlier, the popular IAMs are built on enumerative studies that estimate climate damages to a particular economic (or non-economic) sector of a geographical region in a specific time period. These studies, for the most part, omit dynamic considerations with respect to damages. As a consequence, the current IAMs based upon these estimates fail to model the potential effects of climate change on economic growth—a dynamic phenomenon—and instead focus on the effect of climate change on the level of output (Fankhauser and Tol, 2005, Tol, 2009; Moyer et al., 2013).[53]

In their default versions, the popular IAMs (DICE, FUND, and PAGE) all assume the relentless march of output growth. In FUND and PAGE, regional GDP per capita growth rates (and total factor productivity growth) are exogenous inputs into the models that are determined by the economic and population scenarios chosen by the modeler. As a consequence, climate change affects consumption only. In DICE, economic growth (increased GDP due to all factors including changes in inputs—labor and capital—and technological progress) is endogenous and total factor productivity growth (increased GDP due solely to technological progress) is exogenous. As a consequence, climate change potentially affects the growth path by decreasing the marginal production of capital (and as a consequence the optimal savings rate) and decreasing output (and as a consequence decreasing the total amount of investment and capital accumulation) for a given savings rate (Fankhauser and Tol, 2005).[54] However, in DICE, climate change still only has an indirect effect on growth because there are no direct effects of climate change on the inputs of production or total factor productivity. Just as climate change cannot significantly affect the economic trajectory of the global economy in DICE as currently specified, Moyer et al., (2013) shows that climate damage eight to 17-fold higher does not contract economic output by 2300 in DICE. Furthermore, in the U.S. government analysis, the IWG modify DICE to have an exogenous savings rate, such that, like FUND and PAGE, climate change affects only consumption.[55]

The consequence of this unthreatened growth path is that it is not optimal to divert resources for mitigation purposes in the short-run, but rather to continue higher levels of current consumption (and, according to DICE, current investments in capital) (Moyer et al., 2013). In this scenario, the future is always richer than the present due to a growth path of per capita consumption that is rarely overwhelmed by climate change. As a consequence, the discount rate (through the Ramsey equation) almost never declines rapidly, though this prospect is unlikely according to Fankhauser and Tol (2005).[57,58]

While most IAMs provide estimates of declines in output in the present period and do not analyze the implications of climate change for stable, long-term economic growth, climate change may also affect economic growth of economies (Tol, 2009). In general, the risk of climate change creating long-term implications for economic growth are particularly relevant for less developed countries characterized by low reserves of financial capital (Dell, Jones and Olken, 2008; Aziadaris and Stachurski, 2005). In other words, recent research asks whether the exogenous growth assumption is valid, particularly for developing nations. Dell, Jones, and Olken (2012) find a 1.3 percent decline in the economic growth rate of poor countries for a 1 degree Celsius increase in annual average temperature.[59] Hsiang (2010) finds an overall decline of 2.4 percent for a 1 degree Celsius increase in Caribbean and Central American countries resulting from declines in the agricultural and non-agricultural sectors. Even small changes in the growth rate, such as 0.6 percent to 2.9 percent declines in the annual growth rate in poor countries would dominate all other economic damage estimates over the three-century timeline of IAMs (as specified in the IWG analysis). In further support of these findings, Jones and Olken (2009) find that a 1 degree Celsius increase in the temperature of a developing nation reduces exports by 2 percent to 5.7 percent.

There are several mechanisms through which climate change can directly affect economic growth. First, poor regions may suffer from further depleted funds due to climate change and be unable to adapt to rising temperatures and other climatic changes. This could result in a poverty trap (Tol 2009). Second, climate change could affect growth rates via a rise in social conflict (Tol 2009). While social conflict may affect economic growth, particularly political violence (Butkiewicz and Yanikkaya 2005), it is unclear by which mechanism this effect may occur.[60]

Third, there is evidence that climate change will directly affect labor productivity through work capacity limits (that is, a physical and/or mental limit on the amount of time or effort that individual can expend in a given day),[61] irritation, and disease (Lecocq and Shalizi, 2007; Tol, 2009).[62] Dell, Jones, and Olken (2012) summarize much of this literature, including lab experiments and natural experiments, to find that "labor productivity losses ... center around 2 percent per additional 1 degree when baseline temperatures exceed 25 degrees." These studies generally focus on indoor employment where adaptation is possible, but productivity losses are more substantial for outdoor labor, such as agriculture, and labor intensive industries in non-climate-controlled environments where adaptation to higher temperature and/or avoidance of rain is difficult (Hsiang 2010; Dell, Jones, and Olken 2012). Furthermore, decreased output from climate change could also decrease labor productivity via investments in labor productivity and/or human capital (Fankhauser and Tol, 2005).

In recent work that assumes no adaptation (including increased use of air conditioning), Kjellstrom et al., (2009) estimates labor productivity losses from climate change (resulting from work capacity limits and not an increase in the number of sick days) of up to 11.4 percent to 26.9 percent in some developing regions of the world by 2080. These losses are somewhat reduced when accounting for shifts in regional labor forces between the agriculture sector to industry and service sectors. Using regionalized estimates from Kjellstrom et al., (2009), the authors of ENVISAGE, an alternative IAM, find that declines in labor productivity are of paramount importance in terms of economic damages (accounting for at least three-quarters of all damages). Labor productivity accounts for about 84 percent of total global damage in 2050 and 76 percent in 2100, which is equivalent to a 1.5 percent decline in GDP in 2050 and a 3.5 percent decline in GDP in the year 2100 (Roson and van der Mensbrugghe, 2010).

Fourth, labor supply may potentially fall as labor productivity declines. Most IAMS assume an exogenous labor supply equal to population, such that the labor supply grows according to an exogenous path. However, in labor intensive industries, Zivin and Neidell (2010) find a decrease in the labor supply by as much as one hour at temperatures above 85 degrees Fahrenheit.[63] While there is evidence of partial acclimation and the strong potential for adaptation, accounting for adaptation fully may be difficult because it includes: temporal choices (shifting activities to different times of the day and/or different days of the week), activity choice (for example, shifting activities indoors), location choice (for example, moving), and climate neutralizing technologies (for example, using an air conditioner). Furthermore, the labor supply may further decline if a rise in morbidity from climate change forces individuals out of the labor force, or a rise in mortality from climate change decreases the potential labor force (Fankhauser and Tol, 2005).

Fifth, higher temperatures, increased intensity of storms, rising sea-levels, and tipping point events will increase the capital depreciation rate through losses of the capital stock and decreases in the longevity of capital (Hall and Behl, 2006; Fankhauser and Tol, 2005). Losses in capital stock are likely to result from sudden changes, such as from storms and tipping points, rather than slow changes that would allow for adaptation via the movement of capital (Hall and Behl, 2006). For example, Freeman (2000) cites potential capital stock losses of 1 percent, 5 percent, 12 percent, and 31 percent for a one in 10-, 50-, 100-, and 500-year storm, respectively, for Honduras. Another example is Hurricane Andrew and Hurricane Iniki in 1992, which combined to reduce the U.S. capital stock by $55 billion (Cashell and Labonte, 2005). While the overall economic effect of natural disasters is debated (due to positive effects of reconstruction and remittances), it is clear that storms negatively affect growth through declines in the capital stock and that larger storms (which are more common under climate change) have overall negative effects (Fomby, Ikeda, and Loayza, 2011; Hochrainer, 2009).[64]

Sixth, climate change could also affect economic growth via the capital stock through investment decisions. On the one hand, climate change could influence the relative prices of investment and consumer goods. Climate change is expected to affect a variety of market sectors that produce consumer goods and is generally expected to raise prices and decrease output in these sectors. Higher prices for consumer goods and lower levels of per capita output would lead to lower levels of consumption, while increased future prices could influence investment levels upward (Jorgenson et al., 2004). On the other hand, climate change could lower the amount of output available for investment, which would decrease the amount of capital via capital accumulation. Furthermore, decreases in the labor force and population from climate could decrease the amount of savings available for investment (Fankhauser and Tol, 2005).

Seventh, forward-thinking agents may also change their investment decisions due to the expected effects of climate change. However, it is unclear in which direction. On the one hand, forward-thinking agents may invest more now due to expected declines in future incomes. On the other hand, they may invest less due to lower expected returns on investments (Fankhauser and Tol, 2005; Moyer et al., 2013).

Eighth, increases in temperature may decrease capital productivity if we believe that the electricity grid becomes more unreliable with climate change. Ninth, according to Fankhauser and Tol (2005), Scheraga et al., (1993) argue that climate change could have structural effects on the economy by changing the relative size of sectors. This could have an effect on the composition of GDP. Tenth, the combination of declining tax revenue, due to declines in output, and increased investment in adaptation could decrease non-adaptation investments that grow the economy. In other words, climate change adaptation, particularly in terms of restoring or producing lost ecosystem services, drains capital and labor from research and development (Fankhauser and Tol, 2005; Moyer et al., 2013).

Last, an argument can be made for adding land to the production function. While this is not an input into production in the neoclassical growth model, it is one of the three factors of production in most political-economic work that predates the marginal analysis revolution. This would add additional channels through which climate change could affect economic growth: declining land due to sea level rise and the loss of ecosystem services. This would allow for the loss of ecosystems to have more than a temporary effect on the economy.

Only DICE can be easily modified to capture these changes in growth. In FUND and PAGE (and DICE in the IWG analysis), it is difficult to model changes in the GDP growth rates due to climate change because economic growth rates are determined by an exogenous socio-economic scenario, as discussed above. In these models, the inclusion of the effects of climate change would require a change in the socio-economic scenario; this would make modeling the marginal effects of an additional unit of CO_2 more difficult. However, it is possible.

Modeling the effects of climate change on economic growth in an endogenous growth model, like DICE, is much easier although it requires the specification of a particular mechanism through which climate change may affect growth. As discussed above, DICE, as specified by Nordhaus and not IWG, is the only one of the three IAMs to use an endogenous growth model to estimate climate damages. DICE, as originally intended by Nordhaus, examines climate change using a variation of the Cass-Koopmans model with a single good that can be used for either consumption or saving/investment.[65] However, while DICE does allow for endogenous economic growth, all shocks are to consumption via a general shock to GDP; there are no shocks to labor, capital, or total factor productivity. Thus, modeling the effects of climate change on economic growth via the mechanisms discussed above will require modifications of DICE's structure. As currently specified, the endogenous economic growth structure of the DICE model, which allows for capital investment through an increased savings rate and investment in carbon abatement, allows for some mitigation of climate damages via: (1) increased capital investment that can offset climate damages to output, and (2) substitution of consumption for a reduction in carbon emissions (Nordhaus, 2011; Nordhaus and Sztorc, 2013).[66]

Moyer et al., (2013) modifies DICE-2007 in two different ways to capture the effect of climate change on total factor productivity corresponding to the Cobb-Douglas production function that represents global economic output. First, Moyer et al., (2013) modify DICE such that a portion of climate damages affects the level of total factor productivity. As a consequence, climate damages affect output and economic growth. The authors find that even a small diversion of damages to total factor productivity can produce negative economic growth rates, such that even one-quarter of damages affecting total factor productivity can result a devastatingly high social cost of carbon dioxide of $1,600. Second, they modify DICE such that climate damages reduce the growth rate of total factor productivity. As specified, total factor productivity cannot shrink as to produce economic contractions, and instead is limited to stalling economic growth. While this specification of the damage function does not result in economic collapse from climate change, like the previous specification, it implies an unequivocal increase in the SCC. From these results, Moyer et al., (2013) conclude that modeling the effects of climate change on economic growth can be as important as the discount rate in determining the magnitude of the SCC.

Two alternative IAMs, ENVISAGE and ICES, model the effects of climate change on economic growth (via shocks to labor, capital, and total factor productivity) in a general equilibrium model, GTAP. The authors of ENVISAGE model several damage sectors: agricultural, sea level rise, water, tourism, energy demand, human health and heat-related labor productivity.[67] Unlike DICE, FUND, and PAGE where climate damages affect consumption directly, climate change affects economic output through effects on labor, capital, and land productivity and stock, multi-factor productivity (that is, total factor productivity), and energy and tourist demand (Van der Mensburgghe, 2008). Depending on the damage sector, these shocks to productivity, input availability, and consumer demand can be heterogeneous and homogenous across economic sectors, that is, economic activities (Van der Mensburgghe and Roson, 2010). Using ENVISAGE, Roson and van der Mensbrugghe (2010) estimate damages of 1.8 percent and 4.6 percent of global GDP for increases of 2.3 degrees Celsius and 4.9 degrees Celsius,

Gonaïves, Haiti, after the hurricanes. Photo: Roosewelt Pinheiro/ABr

respectively, above 2000 temperatures; as noted earlier, labor productivity accounts for about 84 percent of total global damage in 2050 and 76 percent in 2100 (Roson and van der Mensbrugghe, 2010). The authors of ICES model several damage sectors: agricultural, sea level rise, forestry, floods, tourism, energy demand, and human health.[68] In ICES, damages affect economic activity through supply side shocks to capital and land stocks and capital, labor, and land productivity (Bosello, Eboli, and Pierfederici, 2012). Like ENVISAGE, the authors of ICES also model demand shocks to tourism and energy demand in addition to supply shocks. Bosello et al., (2012) estimate a 0.5 percent decline on global GDP for a 1.9 degrees Celsius increase in global temperatures relative to pre-industrial temperatures.

Non-market damages

Yohe and Tirpak (2008) and Tol (2009) note that many non-market damages are still missing from current estimates and need further study. Among these are the non-market impacts of ocean acidification (as mentioned earlier), the loss of ecosystem services, the loss of biodiversity, and the omission of some health costs (Tol, 2009). While not an omitted damage per se, the default versions of the IAMs also fail to capture the increase in the value of non-market commodities relative to market goods due to their increase in scarcity. This failure results in a systematic underestimation of non-market damages, particularly biodiversity and ecosystem services, as the value of losses increase.[69]

ECOSYSTEM SERVICES. Natural ecosystems provide a multitude of services that benefit humanity, which are collectively known as ecosystem services. Many of these services are essential for human existence. The United Nations Millennium Ecosystem Assessment groups ecosystem services into four types: (1) provision (food—crops, livestock, fisheries, aquaculture, wild plant and animal products; fiber—timber, cotton, hemp, silk, wood fuel; genetic resources; biochemical, natural medicines, and pharmaceuticals; ornamental resources; fresh water), (2) regulating (air quality regulation; climate regulation—global, regional, and local; water regulation; erosion regulation; water purification and waste treatment; disease regulation; pest regulation; pollination; natural hazard regulation), (3) cultural (cultural diversity; spiritual and religious values; knowledge systems; educational values; inspiration; aesthetic value), and (4) supporting services (soil formation, photosynthesis, primary production, nutrient cycling, and water cycling). The ecosystems that provide these services are known as natural capital; their value equals the present value of all future streams of ecosystem services.

By the end of the century, climate change will be the most important driver of natural capital loss, ecosystem change, and ecosystem service loss. While some regions may experience some initial benefits from climate change in terms of increased ecosystem service provision, overall, the globe will experience negative effects and eventually all regions will experience losses (Millennium Ecosystem Assessment; IPCC, 2007). While not all services are affected by climate change, many of them are. Of these services, only a few are currently included in the IAMs.

Some ecosystem services are already accounted for in the social cost of carbon via other damage sectors. Some of these ecosystem services are explicitly captured by all three IAMs. For example, food and fiber services (particularly crops, livestock, and timber) are explicitly captured via the agricultural, forestry, and "other market" sectors.[70] Some ecosystem services are only captured by some IAMs. For example, only PAGE09 and early versions of DICE explicitly include climate regulation services (particularly globally) in their estimates of the social cost of carbon via their tipping point and catastrophic damage functions, respectively; see the catastrophic damage section below for further discussion.[71] Finally, some ecosystem services are clearly excluded from the default versions of current IAMs, such as pest regulation and pollination as discussed earlier.[72] Some of these omitted services can be thought of as examples of inter-sector services from the non-market sector to the market sector, and will be discussed indirectly in the subsection on the omission of inter-sector damages.

It can be difficult to determine whether ecosystem services are already captured via existing damage functions for two reasons. First, whether an ecosystem service is captured in the damage function(s) is dependent on whether the source of the damage estimate accounted for this service. For example, it could be potentially argued that water purification and water cycling services of ecosystems are already captured in FUND and early versions of DICE (and thus PAGE09, which includes estimates from both other IAMs) via the water sector and the "other market" sectors, respectively. However, this is only true if the water purification and cycling services of ecosystems are directly measured by the underlying studies used to calibrate these models, and this is not the case. In the case of water purification services, forested catchments supply 75 percent of the globes fresh water supplies (Shvidenko et al., 2005; IPCC, 2007 – Chapter 4), and these services could potentially be accounted for in the underlying forestry damages. While the forestry sectors in both models account for the effect of climate change on the value of timber sales, the water sector (within the "other market" sector in DICE-1999) fail to explicitly account for the water purification services of ecosystems. Thus, none of the three IAMs are likely to capture the effect of climate change on the water supply via its effect on forest ecosystems.[73]

Second, some of these omitted services, including water purification and cycling services, may be captured in general attempts by IAMs to capture the value of natural capital. In FUND 3.5 to 3.8, ecosystem damages from climate change are based on a "warm-glow" effect whereby the population's valuations of damages are independent of any real change in ecosystems (Anthoff and Tol, 2012). The warm glow effect is measured by how much people say they are willing to pay for services resulting from habitat preservation services (for example, to preserve wildlife), and Tol (2002) explains that the effect "suggest that people's willingness to pay reflects their desire to contribute to a vaguely described 'good cause,' rather than to a well-defined environmental good or service." However, Anthoff and Tol (2012) calibrate the ecosystem damage function to estimates from Pearce and Moran (1994), who report a mean willingness to pay of $50 per person in OECD nations for habitat. While Pearce and Moran use the $50 value to specifically value loss of habitat services (for example, to preserve species), FUND generalizes this figure to be a warm-glow valuation of people's willingness to contribute to the environment as a societal good. However, this extrapolation is not valid: Tol excludes many of the non-habitat services of ecosystems from FUND because these estimates are based on provision of habitat services by ecosystems and not the other tangible and intangible ecosystem outputs.[74] Therefore, FUND likely omits the value of many ecosystem services.

Alternatively, Nordhaus and Boyer (2000) use their own discretion to determine regional economic damages from climate change to ecosystems in DICE-1999 (also one of the sources used to calibrate the default version ofPAGE09); the authors develop their own rough estimates of the loss of natural capital because of the highly speculative nature of estimates. The authors assume that the capital value of the portion of human settlements and ecosystems sensitive to climate change is between 5 percent and 25 percent of regional GDP depending on their size, mobility, and robustness and sensitivity. It is further assumed that a region's annual willingness to pay to prevent climate damages to human settlements and ecosystems equals 1 percent of their capital value, "which is one-fifth of the annualized value at a discount rate on goods of 5 percent per year (Nordhaus and Boyer 2000)." Therefore, the default version of PAGE09 partially captures some of these "omitted" ecosystem services. However, it is impossible to tell to what extent because (1) the PAGE09 default damage functions are also greatly informed by damage estimated from FUND, in addition to DICE-1999, which potentially only captures the value of habitat services (as discussed in previous paragraph), and (2) it is impossible to tell what damages to ecosystem services are omitted from the DICE-1999 climate damage estimates because of the speculative nature of this valuation.

In DICE-2013, the value of natural capital is likely excluded (or at best partially captured) due to a failure of many of the underlying studies to consider them, particularly the studies that only capture market damages.

BIODIVERSITY. The habitat services of ecosystems may or may not include the value of biodiversity in some IAMs. By the end of the century, climate change will be the single most import driver in biodiversity loss (Millennium Ecosystem Assessment). According to the IPCC (2007), "approximately 20-30% of plant and animal species assessed so far are likely to be at increased risk of extinction if increases in global average temperature exceed 1.5-2.5°C." Given the significant species loss that could occur by the end of the century and the likelihood of continued biodiversity loss with even higher temperatures thereafter, accurate estimates of the value of biodiversity loss are essential.

Tol (2009) considers biodiversity loss to be among the largest of the omitted impacts of climate change. Economists not only struggle to place a value on biodiversity, but they also lack the understanding of how climate change will affect intricate systems and processes like nutrient cycles. Furthermore, rather than occurring more gradually as does sea level rise, biodiversity loss is likely to be characterized by a series of system failures and ecological shocks, making it even more difficult to model (Tol 2009). Thus, current default versions of the IAMs may be omitting the value of biodiversity loss. This statement may seem inconsistent with Tol's FUND model given the inclusion of biodiversity loss in FUND 3.6, as a function of species loss (that is, the value of biodiversity increases with the loss of species) and temperature change. However, Tol (2009) is essentially arguing that future work is necessary to improve the accuracy of the estimate of the value of biodiversity, and he will continue to use the warm glow effect (as discussed in the previous section) in FUND until a better estimate becomes available.[75,76]

Like ecosystem services in general, it is unclear how extensively the default versions of the other two IAMs, DICE-2013 and PAGE09, account for biodiversity. These are for the same reasons as discussed in the previous subsection.

OMITTED HEALTH COSTS. According to Tol (2002a), morbidity and mortality can be directly influenced by climate in six ways: (1) high and low temperature (that is, heat and cold stress), (2) vector-borne infectious disease (3) non-vector-borne infectious disease (including, zoonotic and waterborne diseases (NIH 2010) (4) air quality, (5) floods and storms, and (6) inter-sector effects of agriculture and water quality. A seventh path of influence, which is missed by Tol (2002a), is humanity's socially contingent response to climate change, including forced migration, political and civil unrest, and increased violence.

None of the three IAMs discussed by the IWG includes all categories of damages. DICE-1999, which is utilized as a damage source in the default version of PAGE09, focuses on air pollution and the expansion of the geographical distribution of tropical diseases, including vector-borne diseases (malaria, dengue fever, trypanosomiasis, Chagas disease, schistosomiasis, leishmaniasis, lymphatic filariasis, and onchocerciasis) due to higher temperatures (Nordhaus and Boyer, 2000). Second, FUND 3.6, earlier versions of which were also utilized as a damage source in the default version of PAGE09, captures mortality and morbidity from four sources: diarrhea, vector-borne diseases, cardiovascular and respiratory disorders, and storms (Anthoff and Tol, 2012). Within the causes of health damages considered in FUND, however, modeling assumptions omit relevant damages. For example, heat-related cardiovascular mortality and morbidity is limited to urban areas, but we see no reason to ignore these effects within rural populations (Ackerman, 2010). Additionally, "the total change in mortality is restricted to a maximum of 5% of baseline mortality (per cause)" (Anthoff and Tol, 2012); under high levels of warming (for example, 6 degrees Celsius), this may be an unjustifiable restriction that will bias social cost of carbon estimates downward. Last, it is unclear what health damages are included in DICE-2013 because of its meta-analysis structure, and because several studies utilized in the analysis rely on statistical methods that are less explicit in what types of health costs are captured.

Early versions of DICE, upon which the default version of PAGE09 is partially based, and recent versions of FUND are not consistent in what types of health damages are included. On the one hand, DICE-1999 excludes many negative health effects of climate change captured by FUND: diarrhea (fourth and eleventh leading cause of death worldwide in 1990 and 2020, respectively, according to Murray and Lopez [1997]), cardiovascular disorders, respiratory disorders, tropical storms (hurricanes and typhoons), and extra-tropical storms (cyclones). Additionally, DICE fails to account for the cost of morbidity. On the other hand, FUND fails to account for declining air quality due to pollution that results from climate change, some of which DICE-1999 captures.

There are many health effects that DICE or FUND, and thus likely PAGE, omit. This includes: mortality and morbidity from the combined effects of storms and rising sea levels (that is, coastal flooding), flooding more generally (inland flooding from flash floods and the overflow of rivers), mortality, morbidity and air pollution effects from forest fires, non-vector-borne infectious diseases, some vector borne infectious diseases (like Lyme disease), and decreased air quality due to pollination; decreased labor productivity due disease and increased heat (see the subsection above of the effects of climate change on the economic growth rate for further discussion); and indirect health damages from climate change via agriculture and water resources (Ackerman and Munitz, 2012; Hanemann, 2008; IPCC, 2007; Tol, 2002; WMO, 2006). Finally, violence (the 16th and 14th leading cause of death worldwide in 1990 and 2020, respectively, according to Murray and Lopez, 1997) and war injuries (the 20th and 15th leading cause of death worldwide in 1990 and 2020, respectively, according to Murray and Lopez, 1997) may increase if social conflicts arise due to climate change.

There are also general equilibrium effects of health damages that are omitted by the IAMs. Tol (2009) referring to the results of his own paper, Bosello, Rosen, and Tol (2006), states that "the direct costs are biased towards zero for health, that is, direct benefits and costs are smaller in absolute value than benefits and costs estimated by a general equilibrium model. This is because countries that would see their labor productivity fall (rise) because of climate change would also lose (gain) competitiveness, so that trade effects amplify the initial impact." Therefore, the exclusion of these general equilibrium impacts may further bias the health damages included in IAMs further downwards.

RELATIVE PRICES. Climate change is predicted to affect market and non-market goods produced outdoors (such as agricultural, fisheries, forestry, and environmental goods and services) more than market goods produced indoors; market goods insensitive to climate change account for the majority of GDP (Nordhaus and Boyer, 2000). As a consequence, outdoor produced goods will become relatively scarcer than indoor produced goods over time. Based on the law of scarcity, the value of outdoor produced goods and services will increase relative to indoor produced market goods. However, current damage estimates to climate sensitive goods and services reflect the current ratio of their economic value to climate insensitive goods, which is based on the current ratio of their quantities. By extrapolating these estimates to future time periods without making any explicit adjustment for relative prices, that is, without accounting for relative change in value of outdoor produced goods and services to indoor produced goods over time, the developers of IAMs implicitly assume constant relative prices, and bias the SCC downward.

A methodically sounds way to address this issue is to explicitly model relative prices. However, most IAMs (including DICE, FUND, and PAGE) include only an aggregate consumption good, as measured by per capita consumption, in the social welfare function.[77] On the consumer side of the economy, this assumption implies all goods and services, including market goods and non-market goods, are perfectly substitutable (even in the long-run), and that they have constant relative prices (Gerlagh and van der Zwaan, 2002; Sterner and Persson, 2008). Constant relative prices imply the ratio of the prices of any two goods must remain constant, regardless of the amounts available of either good.[78] As a consequence, the current IAMs fail to capture the increase in value of outdoor produced goods and services relative to other traditional consumption goods produced indoor (Gerlagh and van der Zwaan, 2002; Sterner and Persson, 2008).[79] Therefore, the simplifying assumption of modeling only one generalized consumption good biases the social cost of carbon estimates downward because future damage estimates to climate sensitive goods and services fail to account for the increase in relative value of these goods and services, as discussed in the previous paragraph.

Recent work has looked at the effect of disaggregating per capita consumption into market goods and non-market goods. Developing a simple social welfare function with two sectors (market and non-market) that grow at different rates, Hoel and Sterner (2007) find that increasing consumption of market goods and constant or decreasing consumption of environmental services will increase the relative value of environmental services due to their increasing relative price when the elasticity of substitution is less than one, that is, it is difficult to substitute market goods for non-market goods.[80,81] Hoel and Sterner (2007) demonstrate, as Gerlagh and van der Zwaan (2002) did before them, that the value of market goods will collapse to zero in the long run if these paths continue. After deriving an updated equation for the discount rate (similar to the Ramsey equation) resulting from the new specification, Hoel and Sterner (2007) also find that the combined effect of a newly derived discount rate and the change in relative prices can result in damage estimates that exceed those calculated under traditional discounting.[82] The work in Hoel and Sterner (2007) applies to any two sectors of the economy, not just market and non-market goods.[83]

To capture these effects on the optimal emissions path, Sterner and Persson (2008) modify DICE to restrict substitutability between non-market and market goods. Like Hoel and Sterner (2007) and Neumayer (1999) before them, Sterner and Persson (2008) find that allowing a change in relative prices can increase the costs of climate change relative to a model assuming constant relative prices. More specifically, the authors find that damages double from 1.05 percent of GDP for a 2.5 degree Celsius increase to 2.1 percent of GDP; this implies that the SCC would also increase with a switch away from constant to relative prices. Using their base parameters, Sterner and Persson (2008) also find that allowing for a change in relative prices achieves a lower optimal emissions path than the Stern Review (Sterner and Persson, 2008; Heal, 2009).[84] In this sense, relative prices can be as important as the discount rate in determining the optimal climate change prevention policy. However, their results are highly dependent on the assumed elasticity of substitution. The lower the actual elasticity of substitution is, that is, the more difficult it is to substitute market goods for lost non-market goods to make society as equally well off under climate change, the more likely the current integrated assessment models are to underestimate the environmental cost of climate change by assuming perfect substitutability.

As is common in these models, we are left with uncertain parameters determining the optimal level of conservation. In this particular case, this is the elasticity of substitution. This recasts the argument about whether or not to act now from a disagreement about the discount rate into a debate of whether poor (strong) sustainability or perfect (weak) sustainability, that is, an elasticity of substitution less than or greater than 1 in the context of the CES utility function, holds in the long run (Gerlagh and van der Zwaan, 2001). Unlike the pure rate of time preference and the elasticity of the marginal utility of consumption, the elasticity of substitution is not an ethical parameter. However, there is still considerable uncertainty about this parameter due to a lack of empirical data (Neumayer, 1999). Sterner and Persson (2008) argue that a lower elasticity of substitution is more likely because some environmental goods are unique and irreplaceable (for example, drinking water), and these goods are likely to dominate the calculation of the elasticity of substitution as environmental goods become more scarce. In a similar argument, Heal (2009) states that market goods and environmental services are complements because some of the services in the former group are irreplaceable and essential to life (Heal, 2009; Dasgupta and Heal, 1979). Heal (2009) points out that this has two implications: some level of environmental services is essential and that the elasticity of substitution is not a constant.[85] Gerlagh and van der Zwaan (2002) demonstrate that even if the substitutability varies with the amount of environmental services, there often exists a level of environmental services below which poor substitutability occurs in the long run. While these arguments support an elasticity of substitution below which it is difficult to substitute consumption goods for environmental goods (elasticity of substitution of less than one), future debate is likely to ensue as current statements are more a matter of belief due to a lack of empirical evidence (Neumayer, 1999).

Greenland ice loss exceeds that of Ice gain. Photo:Christine Zenino, Chicago, US

All three IAMs include only an aggregate consumption good in the social welfare function, and so assume constant relative prices and perfect substitutability. While FUND 3.6 does account for the increase in the relative value of habitat services due to the loss of species, this is done in a limited way. Therefore, all three IAMs systematically underestimate climate damages to non-market commodities, possibly by a large margin.

Socially contingent damages

Many social scientists and economists have argued that the ill-effects of damages to commoditized goods from climate change will extend beyond the calculated loss of value to affect societal dynamics (U.S. Climate Change Science Program, 2008). For example, agricultural damages account for the value of diminished productivity and lost crops, but not for the social repercussions of food insecurity and famine. In many regions, shifting weather patterns, rising sea levels, and increased natural disasters will threaten infrastructure, habitable lands, crop yields, and water resources. Under the resulting intensified resource competition, individuals will have to choose among adapting to resource scarcity, relocating to a region with more abundant resources, or using force to secure a share of the available resources. Each coping pathway has implications for political and social stability (Buhaug, Gleditsch & Theisen, 2009).

The IPCC, which once included social consequences (such as migration) as direct consequences of climate change, has since revised its stance, focusing instead on "human vulnerability," a measure expressing the relative risk of welfare impacts of climate change for individuals and communities (Raleigh & Jordan, 2010; IPCC, 2001). Vulnerability is determined both by physical factors (for example, drought likelihood) and social factors (for example, social status). Highly vulnerable societies are less likely to succeed in their adaptation efforts, and consequently, more likely to resort to conflict and migration. Adaptation strategies used in poorer regions such as removing children from school to provide additional income or subsisting on fewer resources, diminish the welfare of those employing them, and thereby increase the incentives for migration or armed conflict over time. Homer-Dixon (1999) argues that the developing world is more vulnerable to resource scarcity because the "innovation gap"—the difference in capacity between those who are able to innovate solutions to resource scarcity and those who are not—is largely dictated by the financial, physical, and human capital stores and the capacity to mobilize them. As a consequence, developing countries are much more likely to be susceptible to social and political instability from climate change (Homer-Dixon, 1999).

The study of climate change's social impacts is still emerging despite a lack of ability to predict their severity or likelihood. The risks of these broader, complex social responses to climate change are poorly understood and difficult to anticipate, and historical studies are of little use given the unprecedented nature of climate change. In particular, because climate change is a contributing factor and not the direct cause of migration and conflict, isolating the role and corresponding social damages of climate change is especially difficult (Homer-Dixon, 1999; Buhaug, Gleditsch & Theisen, 2008). In addition, the identification strategies of many papers are confounded by various statistical difficulties (Dell, Jones, and Olken, 2013).

Partially as a result of this difficult identification problem, the most recent versions of the three IAMs used by IWG do not address socially contingent damages, such as migration, social and political conflict, and violence. The one exception is FUND, which partially accounts for this social cost indirectly by modeling migration from permanent flooding. However, as discussed under inter-regional damages, FUND ignores most of the costs of migration, including the social conflict caused by an influx of migrants.

MIGRATION. Increases in labor migration and distress migration are likely results of increasing temperatures, reduced rainfall, shorter growing seasons, and sea level rise. Labor migration, generally driven by the “pull” force of economic opportunity, is common in many societies and can play an important role in the adaptation of communities by diversifying income sources and providing supplemental income through remittances. Distress migration, driven by the “push” force of local calamity, tends to be a coping mechanism of last resort. Labor migration is particularly sensitive to climate change-related factors, especially those that are gradual or chronic, which increase the need for income diversification and the allure of economic opportunities elsewhere. Distress migration only increases under sudden shifts, such as natural disasters (for example, severe storms) or irreversible changes (for example, permanent flooding from sea level rise). Distress migration is also more sensitive to social factors than labor migration. The ease of evacuation and availability of relief affect the rates of distress migrations, while community support, economic opportunities, and governmental policies influence resettlement rates. The severity and permanence of damage also play important roles in determining rates of migration and relocation (Raleigh & Jordan, 2010).[86]

It should be noted that mass migration, as predicted by many analysts, may also have significant effects on non-market goods and services. Specifically, mass migration into lesser affected areas may result in damages to environmental goods and services to the incoming nations (Oppenheimer, 2013). This type of damage would qualify as an inter-sector effect, which is discussed in a following section.

CONFLICT. In large scale crises, such as climate change, conflict tends only to occur in societies with histories of armed violence and deep political and social fragmentation. The developing world, which is slated to bear the brunt of climate change due to a lack of adaptive capacity, is considered especially vulnerable to climate-change-related social crises because their economic and political institutions tend to be less stable than those of the developed world (Millner & Dietz, 2011; Buhaug, Gleditsch & Theisen, 2008). Lower availability of financial resources and insurance also tend to increase the rate and permanence of climate change damages in developing countries, making conflict more likely, and intensifying existing conflicts (Millner & Dietz, 2011).

Buhaug, Gleditsch and Theisen (2008) advance four narratives on how climate change can drive conflict by contributing to political instability, economic instability, migration, or inappropriate governmental response. Climate change can exacerbate political instability when weak political institutions fail either to adequately address climate-related catastrophes (droughts, famines, and so on) or to deliver other public goods (such as healthcare, education, and infrastructure) because remediating such catastrophes diverts significant resources. Climate change can contribute to economic instability when decreased availability of a renewable resource drives down household incomes, which can compound existing intergroup inequalities and reduce the governmental funds available to adapt to climate change. [87] Migration driven by natural disasters or sea level rise could cause influxes of climate refugees, increasing environmental, economic, social and political stresses in receiving areas, particularly when the incoming refugees are of a different nationality or ethnic group. Finally, unpopular responses to climate change, such as draconian emission reduction mandates, could result in social uprisings in response. Dell, Jones, and Olken, (2013) also highlights the possibility that weather can directly lead to conflict through “changing the environment” or increasing human aggression.

There is literature studying the effect of weather and social and political conflict that is summarized quite thoroughly in Dell, Jones, and Olken (2013). In particular, there are a variety of cross-country and subnational studies which indicated that higher temperatures and lower-than-average precipitation (including droughts) cause civil conflicts and political instability (for example, coups), particularly via the lower household income mechanism. While there are various studies showing the effect of weather on social and political conflict, there is some ambiguity in the effect because of (1) the low explanatory power of weather of conflict (that is, the noise), (2) a variety of statistical problems, including endogenous controls and spatial correlation, (3) the difficulty of measuring weather, particularly precipitation due to the negative effect of too much (for example, floods) and too little (for example, droughts), and (4) the difficulty of determining if weather changes the timing of conflict or actually causes conflict.

Two important recent papers identifying the connection between climate change and social and political conflict are: Hsiang, Meng, and Crane (2011) and Hsiang, Burke, and Miguel (2013). Hsiang, Meng, and Crane (2011) use more than 50 years of data to show that the probability of conflict doubled in the tropics during El Niño years as compared with La Niña years. Based on their analysis, El Niño contributed to 21 percent of the civil conflicts in the tropics taking place between 1950 and 2004, providing some evidence that warmer temperatures do result in more social conflict. This paper is important in that it provides evidence that weather caused more conflict, and displaced only a portion of conflicts over time.[88]

In another study, Hsiang, Burke, and Miguel (2013) conduct a meta-analysis across 60 multi-disciplinary papers.[89] The authors find that the median effect of a 1-standard-deviation change in climate variables over time causes a 13.6 percent change in the risk of intergroup conflict and a 3.9 percent change in interpersonal violence.[90,91] Similarly, precision-weighted average effects, in which studies were down-weighted based on their precision, are 11.1 percent and 2.3 percent, respectively. Even though the magnitude of this effect is heterogeneous (that is, varies over time and space), given that scientists predict a 2- to 4-standard-deviation change in temperature by 2050, possible increases in conflict as the result of climate change are likely to be significant this century in many areas across the globe. In general, the authors find that all types of conflict increase with temperature and precipitation, regardless of the temporal scale, but intergroup violence is less common in rich countries than poor countries.[92] Furthermore, the evidence indicates that adaptation possibilities are limited in that slow-moving climate change still adversely affects conflict, and these effects will continue into the next century. While the authors note that several avenues are possible to connect climate change to social conflict, more research is necessary to select between competing theories on these linkages.[93] Additionally, it is still unclear whether these mechanisms increase the probability of a conflict occurring or the probability of an existing conflict becoming violent.

VIOLENCE AND CRIME. Dell, Jones, and Olken (2013) review the literature studying the effect of weather on violence. In the criminology literature, there is a well-known relationship between higher temperatures and crime, particularly as it relates to aggression. Specifically, many authors find that higher temperatures increase criminal activity, especially as it relates to violent crime. There is an ongoing debate within the literature on whether the cause is neurologically based or a socially contingent response. With respect to precipitation, there is more of a mixed result with some evidence that a lack of precipitation may increase crime and violence through a channel of lower income.

Catastrophic climate change

There is agreement within the literature on the importance of catastrophic damages. However, there is significant debate within the literature about the extent of their importance; see earlier discussion. Regardless of the side one takes, it is clear that these catastrophic damages should be included in IAMs, and the current failure to do so in some IAMs biases their SCC estimates downward. Given Hope's (2013) finding that tipping-point damages can be as important as the sum of economic damages included in IAMs in determining the social cost of carbon, these biases may be significant.

TIPPING POINTS. The IAMs differ in their treatment of climate tipping points. Earlier versions of DICE, that is, DICE-1999, DICE-2007, and DICE-2010, include certainty equivalent damages of catastrophic events as estimated in a survey of experts in Nordhaus (1994a).[94] For the most recent version of the model, that is, DICE-2013, Nordhaus moved to a meta-analysis based on estimates in Table 1 of Tol (2009). Most of these sources do not include tipping point damages, and it is unclear to the extent that they are included in these newer versions of DICE.[95] While DICE-2013 does include the possibility to explicitly model catastrophic damages, it is excluded from the default version of the model (correspondence with Nordhaus).[96]

PAGE explicitly models tipping points in the default version of his model. From PAGE2002 to PAGE09, Hope moved from modeling discontinuous impacts using certainty equivalence to modeling them as a singular, discrete event that has a probability of occurring in each time period when the realized temperature is above a specified temperature threshold (with a central value of 3 degrees Celsius in the default version of the model), and this probability is increasing in temperature. Of the recent versions of the three models, only PAGE09 fully explicitly models tipping point damages; still a risk premium for aversion to such an event is generally not included in the default versions of IAMs (Kouskey et al., 2011).

While PAGE09 and early versions of DICE explicitly model tipping point damages, an alternative, as represented by Lemoine and Traeger (2011), is to implicitly capture tipping point damages by explicitly modeling tipping points. As stated by the authors, they "directly model the effect of a tipping point on climate dynamics rather than approximating its effects by shifting the damage function." Specifically, Lemoine and Traeger (2011) model two broad types of climate tipping points within DICE: (1) increased climate sensitivity (that is, the increase in global surface temperature from a doubling of the CO_2 concentration in the atmosphere) due to increased strength in climate feedback effects beyond current predications, and (2) increased greenhouse gas atmospheric longevity beyond current climate models.[97] It should be noted that this is distinct from modeling fat tails because these modeling changes do not require the use of fat-tailed distributions.

In a similar way, FUND implicitly models tipping points by explicitly modeling the uncertainty of almost 900 parameters in the FUND model.[98] According to Anthoff and Tol (2013a), this captures catastrophic damages more generally by capturing the possibility of catastrophic outcomes, that is, welfare effects. It is unclear to the extent that this method captures tipping points as evidenced by the decision by Hope to jointly model parameter uncertainty and a catastrophic damage function in PAGE09. In other words, FUND may not sufficiently capture catastrophic damages via climate tipping points by simply modeling the uncertainty underlying all parameters in the model.

FAT TAILS. The popular IAMs differ in their ability to capture the catastrophic damages that result from fat tails. However, for the most part, those IAMs fail to model fat tails as suggested by Weitzman. This is because "numerical model(s) cannot fully incorporate a fat-tailed distribution (Hwang, Reynès, and Tol, (2011)."

On the one hand, both FUND and PAGE explicitly model the uncertainty of model parameters by specifying parameter distributions and run Monte Carlos simulations.[99] However, neither model explicitly chooses fat-tailed distributions in its default version. Hope chooses triangular distributions, which explicitly specify minimum and maximums for the probability distribution function, for many of the uncertain parameters in the default version of PAGE; the exception is the climate sensitivity parameter which follows the IPCC (2007) report. In FUND, Tol tends to choose triangular and gamma distributions; the gamma distribution is thin tailed (Weitzman, 2009).[100] However, while Anthoff and Tol (2013a) do not explicitly utilize fat-tail distributions to represent the probability distributions of their 900 uncertain parameters, the distribution of net present welfare from a Monte Carlos simulation of 10,000 runs of FUND 3.6 is fat tailed.[101] While fat tails arise in the distribution of welfare in the FUND model, explicitly modeling parameter distributions as fat tailed may further increase the SCC.

On the other hand, the default versions of the DICE models fail to model any parameter uncertainty. As a consequence, the default versions of all DICE models fail to capture catastrophic damages via the fat tails of uncertain parameters. This is particularly significant when parameters have a right-skewed distribution, such as the climate sensitivity parameter and the possible discontinuity outcomes. Therefore, DICE-2013 mostly excludes catastrophic damages via tipping points and fat tails when parameter uncertainty is ignored.

There have been several attempts to include fat-tailed distributions in the popular IAMs. First, Hwang, Reynès, and Tol (2011) found an increase in the optimal carbon tax when accounting for fat tails in DICE; the optimal carbon tax increases in the uncertainty of the climate sensitivity parameter. Similarly, Ackerman, Stanton, and Bueno (2010) find that fat tails over the climate sensitivity parameter increases the economic costs of climate change, and hence the SCC, in DICE, but the magnitude of this increase is highly dependent on the exponent of the DICE damage function. Second, Pycroft et al., (2011) replaces above the 50th percentile of the original triangular distributions for the climate sensitivity parameter and the damage function (sea level rise, market, and non-market) exponents in the PAGE09 model with thin-tailed (specifically, the normal distribution), medium-tailed (specifically, the log-normal), and fat-tailed (specifically, the Pareto) distributions;[102] they switch off the catastrophic damage function when they modify the distributions of the damage function exponents, decreasing the PAGE09 SCC estimate from $102 in the default version of PAGE to $76, because tipping points and fat tails are related concepts, as discussed earlier in this paper. The authors find that the PAGE09 SCC estimate without a catastrophic damage function increases by 44 percent to 115 percent when medium and fat tails are integrated into PAGE09; this corresponds to an increase from $76 to $135 (thin), $147 (medium), and $218 (fat).[103] Larger percentage increases are observed for the 95th and 99th percentile SCC estimate. In other words, the use of fat-tailed distributions is possible and will significantly increase the social cost of carbon. At the same time, because its value is not infinite, as it is using Weitzman's Dismal Theory analysis, the SCC is still useful for benefit-cost analysis.

By explicitly modeling the probability distribution function of the climate sensitivity parameter using the Roe-Baker distribution, the 2013 IWG analysis may partially capture the effects of fat-tailed distributions; the Roe-Baker distribution used in this analysis is fat-tailed (Pindyck, 2013).

BLACK SWAN EVENTS. All three IAMs may exclude black swan events. While it is unclear how these events could be integrated into these models, it is clear that their exclusion biases SCC estimates downward because scientists believe that bad surprises are more likely than good surprises when it comes to climate change. As discussed earlier, these events may be captured by integrating fat-tail distributions for uncertain parameters into IAMs, but the "correct" fat-tailed distribution is still unknown.

Inter-sector damages

According to both Kopp and Mignone (2012) and the IWG (2010; 2013) IAMs fail to capture inter-sector damages, that is, damages from the interaction of damage sectors. There are a variety of potential inter-sector effects of climate change, and their omission generally tends toward a downward bias. Inter-sector damages include: agriculture and water quality on human health (Tol, 2009; IPCC, 2007); the effects of water supply and quality on agriculture; the combined effects of increased storm strength and rising sea levels (Yohe and Hope, 2013); the effects of ocean acidification on human settlements; and the effects of ecosystem services on the market sector. As mentioned earlier, many of these inter-sector damages include damages that arise from the interaction of climate change effects between sectors in the market-, non-market-, socially-contingent-, and catastrophic-damage categories.

For the most part, the major integrated assessment models (FUND, PAGE, and DICE) calibrate their damage functions, and as a consequence estimate the social cost of carbon, using sector specific studies, or, at least, rely on studies that utilize sector specific damage estimates, that is, enumerative studies.[104] Implicitly, the authors of the IAMs assume that each sector is an island, independent of all other sectors. Therefore, inter-sector damages are captured by IAMs only if the underlying studies account for these inter-sector damages. For example, agricultural studies that account for the effect of climate change on precipitation and the water supply for irrigation will include the effects of the water supply sector on the agricultural sector. However, most damage studies are incomplete as they omit these inter-sector damages (Yohe and Hope, 2013).[105]

The developers of PAGE and FUND argue that these models capture inter-sector effects. On the one hand, Hope (2006) argues that only inter-sector damages between market and non-market sectors, such as ecosystem services, are excluded. Specifically, he argues that all other inter-sector damages are captured because "PAGE2002 models two damage sectors: economic and non-economic. … Using highly aggregated damage estimates from the literature allows PAGE2002 to capture interaction effects implicitly." This is something of a tautology – that is, I utilize generalized aggregate damage functions, and because they are general, I capture interactions. As stated above, inter-sector damages can only be captured if the underlying damage estimates account for them, and they do not in the case of the default version of PAGE09. On the other hand, Tol (2009) goes even further by arguing that IAMs, such as FUND, may be double counting inter-sector damages. For example, the effect of water supply on the agricultural sector may be captured by both the water and agricultural sector damages.[106] Again, this can only be the case if the underlying studies explicitly account for these damages, and this is not the case in FUND due to its reliance on enumerative studies that do not account for inter-sector damages.[107]

The latest versions of the three IAMs utilized by IWG omit inter-sector damages. FUND3.6 and DICE-1999 utilize sector-specific damage estimates (from enumerative studies), and by the arguments above omit most, if not all, of the inter-sector damages excluded from the underlying studies. Because PAGE09 is greatly informed by FUND and DICE-1999, it too omits these inter-sector damages even though it relies on aggregate market- and non-market-damage functions. Finally, DICE-2013 also omits most inter-sector damages. Of the 13 studies underlying the DICE-2013 meta-analysis, eight (Nordhaus, 1994a; Fankhauser, 1995; Tol, 1995; Nordhaus and Yang, 1996; Plambeck and Hope, 1996; Nordhaus and Boyer, 2000; Tol, 2002; Hope, 2006) of them rely on sector-specific calibration techniques (that is, rely on enumerative studies), and omit any inter-sector damages excluded from the underlying studies. Four of the remaining five studies (Mendelsohn, Schlesinger, and Williams, 2000; Maddison, 2003; Rehdanz and Maddison, 2005; and Nordhaus, 2006) utilize statistical technique to estimate the damages from climate change. While statistical methods can capture inter-sector effects, all four of these studies omit the damages from the interaction of market and non-market sectors; Maddison (2003) and Rehdanz and Maddison (2005) only include non-market damages, and Mendelsohn, Schlesinger, and Williams (2000) and Nordhaus (2006) include only market damages. Thus, like the other IAMs, DICE-2013 fails to account for many inter-sector damages.

Wind erosion is evident on this rangeland during severe drought in Arriba County, New Mexico.
Photo by Jeff Vanuga, USDA Natural Resources Conservation Service.

Cross-Sector Damages

As discussed earlier, many of the omitted effects of climate change comprise both market- and non-market-damage sectors. This section discusses omitted climate impacts that affect multiple categories of damages (as opposed to inter-sector damages, where multiple impacts interact to contribute to damages in a specific sector): market, non-market, socially contingent, and catastrophic damages. This includes inter-regional damages, destabilizers of existing non-climate stressors, weather variability and climate extremes, and ocean acidification.

INTER-REGIONAL DAMAGES. Inter-regional damages are spillovers from one region to another. For the most part, the major integrated assessment models (FUND, PAGE, and RICE) estimate the social cost of carbon assuming each region of the world is independent of all other regions. There are a variety of potential inter-regional effects of climate change, and their individual omissions may result in an upward or downward bias. While the individual biases are in both directions, Freeman and Guzman (2009) argue that the overall effect very likely leads to an underestimation of the SCC for the United States.

Freeman and Guzman (2009) lay out several international spillover scenarios with respect to the United States. First, there are potential supply shocks to the U.S. economy in terms of decreased availability of imported inputs, intermediary goods, and consumption goods. This includes energy and agricultural goods. Second, there could be demand shocks as affected countries decrease their demand for U.S. imports. Third, there may be financial market effects as international willingness to loan to the United States dries up and the value of U.S. firms decline as foreign markets shrink. Fourth, mass migration from heavily affected areas, such as Latin America, will potentially strain the U.S. economy, and likely lead to increased expenditures on migration prevention. Fifth, increases in infectious diseases are likely due to the combined effects of ecological collapse, the breakdown of public infrastructure in poor nations, and declines in the resources available for prevention; increasing mass migration will intensify the spread of diseases across borders. Last, climate change is likely to exacerbate security threats to the United States, partially through its potential destabilizing effect on politics. As a consequence, climate change is a “threat multiplier” in terms of security. In summary, there are a variety of pathways for the effects of climate change in one region to cause damages in another: trade, capital markets, migration, disease, and social conflict.

There are also several potential positive spillover scenarios currently excluded from the SCC. First, trade has the potential to reduce the SCC by reducing the welfare losses to consumers in particularly hard hit regions (Darwin, 1995).[109] While consumers in exporting nations and producers in importing nations are harmed by trade, this loss is more than offset by gains to consumers in importing nations and producers in exporting nations according to economic theory. For example, low elevation nations will experience a decline in domestic agricultural production, but importing food from higher elevation nations will mitigate some of the consumer welfare loss from domestic production declines (Darwin, 1995). Through this lens, trade can be thought be as a form of human adaptation to climate change whereby humans move tradable market goods between the least- and most-affected regions to satisfy the needs of those with the highest demand.[110] However, trade can also result in general equilibrium costs, which are also currently omitted (Tol, 2009).[111] Second, technology spillovers between nations may reduce the regional costs of mitigation and/or adaptation. Investment by developed nations into mitigation and adaptation technologies may reduce the costs of mitigation and adaptation in developing nations (Löschel, 2002; Buonanno et al., 2003; Rao, 2006).[112]

The inclusion of inter-regional interactions requires integrating the various regional economic models into an international model. This is technically complex and requires many additional assumptions (Freeman and Guzman, 2009). Care must also be taken to avoid double counting of damages. Rather than simply adding inter-regional damages estimates, modelers have to return to the country-specific damage estimates to examine how they were constructed.

In general, all three IAMs exclude inter-regional damages. There are a few exceptions. First, all three IAMs (DICE-2013, FUND 3.6, and PAGE09) capture general equilibrium effects of trade in the agricultural sector. Second, because GDP measurements include net exports, damage estimates at least partially capture trade indirectly through GDP. Last, FUND models migration as it relates to sea level rise.

FUND 3.6 migration cost estimates are relatively ad hoc and omit several types of damages. First, the method of determining the destination of migrants is ad hoc, and this affects the costs of migration because they are dependent on the destination region.[113] Second, the cost of migration to the sending region is three times its regional per capita income per migrant; Tol (2002) describes three as an "arbitrary" parameter. This approach will underestimate costs of migration if per capita income in coastal regions is greater than the regional average, which would be the case if cities with concentrations of economic activity are affected most by sea level rise. Third, in the region that is receiving migrants, costs per migrant equal 40 percent of per capita income of the receiving country (Cline, 1992 from Fankhauser (1995) from Anthoff and Tol, 2012b); Cline (1992; 120) approximates the costs of migration to the United States based on state and local government infrastructure spending (education, roads, police, sanitation) and taxes paid by immigrants. However, this figure from Cline (1992) was simply an illustration of the cost of migration to the United States and was hardly a "guesstimate," as stated by Fankhauser. Furthermore, these migration-cost estimates exclude the costs of social conflict from migration pressures (for example, the effect of Syrian migrants on Bulgaria), the potential stress on the receiving country's social, environmental, and physical infrastructure under cases of mass migration, the psychological cost to migrants of losing their homeland, and the potential physical health costs to refugees (Fankhauser, 1995). Last, FUND sets intra-regional migration costs equal to zero though there is still likely to be stress on the receiving nations (for example, the effect of Syrian migrants on Lebanon and Jordan from the recent Syrian Civil War).[116]

DESTABILIZERS OF EXISTING NON-CLIMATE STRESSORS. Climate change is often referred to as a threat multiplier. For example, Freeman and Guzman (2009) state that “the consistent message of [national security] studies is that climate change is a ‘threat multiplier’ (Freeman and Guzman, 2009).” While Freeman and Guzman (2009) are mainly referring to national security issues worsening due to climate change further weakening already volatile regions and political unstable nations, their arguments can be generalized to other future challenges that the world faces with or without climate change: social and political instability (Freeman and Guzman, 2009); disease, including the flu (Freeman and Guzman, 2009);[117] ecosystem and biodiversity loss (United Nations’ Millennium Ecosystem Assessment);[118] decreased water availability.[119] In other words, just as the multiple effects of climate change will interact within different economic sectors, as discussed in the previous section under inter-sector damages, non-climate related economic, societal, and environmental pressures will result in multiple damages across sectors due to their interaction with the effects of climate change.

Like inter-sector damages, the interaction of non-climatic factors and the effects of climate change must be captured in the underlying studies utilized to calibrate the IAM damage functions. In most cases, the studies underlying the calibration of the IAMs’ default damage functions do not account for these interactions. Thus, the default versions of the early versions of DICE, DICE-2013, FUND3.6, and PAGE09 by and large omit these damages.

WEATHER VARIABILITY AND CLIMATE EXTREMES. Climate change does not only affect the long-run averages of temperature, precipitation, and sea-level, but also the variability of weather around these changing means. In other words, many more extreme weather events should be expected, including the likelihood of increased: frequency of heat waves, areas experiencing droughts (and some areas experiencing decreased rainfall during monsoons and others experiencing increased aridity), frequency and areas experiencing heavy precipitation events (for example, floods), intensity of tropical cyclones, and extreme high sea level (IPCC, 2007a); see Table 14.

Current IAMs partially capture some of these extremes: tropical storms (hurricanes and typhoons), extra-tropical storms (cyclones), and heat waves. FUND 3.6 explicitly models the economic destruction in terms of lost property and human life (mortality and morbidity) of the increased strength of tropical storms, and the cost to human health (mortality and morbidity) of heat waves, but only to the extent that damages are limited to heat stress. Early versions of DICE, that is, DICE-1999 and DICE-2007, only make an ad hoc account of the loss property, such as human settlements, due to storms in the coastal sector. While both models account for sea-level rise, they fail to account for the interaction between storms and sea level rise, which results in extreme high sea level rise (Yohe and Hope, 2013). As a consequence, the default version of PAGE09 (the damage function of which is greatly informed by FUND and DICE-1999) partially accounts for the cost of the increased intensity of storms and frequency of heat waves. Because most of the underlying studies in DICE-2013 exclude climate extremes, DICE-2013 appears to exclude the economic costs of weather variability (flooding, droughts, and heat waves).

However, these IAMs may implicitly capture some of these extreme events to the extent that these variables are correlated with temperature. Nordhaus (1994a) argues that “in thinking about the impact of climate change we must recognize that the variable focused on in most analyses—globally averaged surface temperature—has little salience for impacts. Rather, variables that accompany or are the result of temperature change—precipitation, water levels, extremes of droughts or freezes, and thresholds like the freezing point or the level of dikes and levees—will drive the socioeconomic impacts. Mean temperature is chosen because it is a useful index of climate change that is highly correlated with or determines the most important variables.” Given that these events are not perfectly correlated with temperature, these events are partially omitted from the analysis. As

Tol (1995) states: "only if the relevant climate parameter relates linearly to the global mean temperature, and the relationship is perfectly known, is the temperature an adequate proxy." Therefore, these events are already included in the IAMs to the extent that global average surface temperature is correlated with these extreme events. To the extent that they are not, they are excluded.

OCEAN ACIDIFICATION. None of the most widely adopted IAMs for estimating the SCC (DICE, FUND, and PAGE) address the multiple damages due to ocean acidification. As defined by Shinryokan (2011): "Ocean acidification refers to a reduction in the pH of the ocean over an extended period, typically decades or longer, which is caused primarily by uptake of carbon dioxide from the atmosphere." In terms of market damages, ocean acidification impacts fisheries via its effects on marine ecosystems and organisms, particularly shellfish and crustaceans. In addition to fisheries, ocean acidification will impact ecosystems, biodiversity, and tourism via its effect on coral and also human settlements. While the economic effects of acidification are likely substantial, few economic values of the damages are available because scientists only recently recognized the threat of ocean acidification to marine life (Guinotte and Fabry, 2009) and fisheries, for the most part, are excluded from IAMs; see previous sub-section.

Though fisheries are expected to suffer significant economic damage as a result of ocean acidification, there are few studies of the economic costs of these impacts. Since 2009, economists have completed several impact studies that attempt to more accurately quantify the economic costs of climate change to fisheries. Two such studies, Cooley and Doney (2009) and Narita et al., (2012), estimate these monetary effects with a focus on mollusk production; recent scientific literature finds that acidified ecosystems significantly reduce mollusk populations. Cooley and Doney (2009) conduct a case study of the effect of ocean acidification on U.S. fisheries revenues, with a focus on mollusks. If there were a reduction of 10 percent to 25 percent in the U.S. mollusk harvest from the 2007 level, $75 million to $187 million of direct revenue would be lost each subsequent year;[120] these values correspond to a net present value loss (that is, the sum of annual losses over all futures years in terms of its current dollar value) of $1.7 billion to $10 billion through 2060. Similarly, using a partial-equilibrium model to assess the welfare loss to society from a decline in shellfish supply, Narita et al., (2012) find that the costs of ocean acidification could exceed $100 billion. Because mollusks represent a small fraction of total fisheries, the cumulative economic impact of ocean acidification on fisheries will likely be significantly larger.

In addition to fisheries, ocean acidification will impact tourism associated with the ocean, particularly coral reefs. Coral reefs are expected to be among the worst-affected ecosystems. A study by Brander et al., (2009) considers the economic damages associated with coral reefs and estimates valuation per area. They expect losses in this sector to be at least $50 billion annually by 2050. It should be noted that the overall effects of climate change on tourism are also excluded, but the magnitude and direction of these effects is uncertain (Tol, 2009; Bigano et al., 2007) and potentially negative (Berrittella et al., 2006).

Adaptation

Some policymakers and analysts may argue that the IAMs need not worry about these omitted damages due to society's ability to adapt. In other words, adaptation implies that these costs will not be incurred. While adaptation must be accounted for when including the above damage estimates, an altogether elimination of these omitted damages (that is, such that they can be ignored) is unlikely. This is particularly the case for non-market, socially contingent, and catastrophic damages, in general, where adaptation is likely be less effective. This is also increasingly the case for market damages as temperatures increase (Hope, 2011). Furthermore, adaptation will be particularly difficult for faster-than-expected temperature increases (Anthoff and Tol, 2012; Hope, 2011). The ability to prevent substantial damages through adaptation is limited as evidenced in current IAM damage estimates.

The current IAMs account for adaptation in different ways. In the early versions of DICE and DICE-2013, adaptation is implicit in the damage estimates.[121] As a consequence, the assumptions about adaptation costs are captured in the underlying damage estimates used to calibrate their damage functions (Warren et al., 2006). While Nordhaus implicitly accounts for adaptation to agriculture, other market, health, coastal, and settlement and ecosystem sectors in the early versions of DICE (DICE-1999, DICE-2007, and DICE-2010)—sometimes in an ad hoc way—he essentially assumes high levels of human adaptation at virtually no cost (IWG, 2010). According to IWG (2010) and Warren et al., (2006), this is particularly evident for the other market sectors. It is less clear the extent to which the DICE-2013 damage function captures these adaptation costs due to the use of a meta-analysis. In all versions of DICE, adaptation is not effective enough to eliminate damages.

In FUND, Tol models adaptation explicitly and implicitly. For adaptation to agriculture, ecosystem, and sea level rise damages, Tol models adaptation explicitly. In the first two of these sectors, Tol captures adaptation by modeling damage costs as a function of the rate of climate change (Anthoff and Tol, 2012); see forthcoming Appendix E. In the case of sea level rise, Tol models the cost of building seawalls. Like in DICE, the assumptions about adaptation costs in the other FUND sectors are captured in the underlying damage estimates used to calibrate these damage functions. Additionally, Tol accounts for adaptation implicitly in the energy and human health sectors by allowing regional sector costs to be a function of regional wealth, such that wealthier societies are better able to adapt (IWG, 2010). According to Warren et al., (2006), FUND assumes perfectly efficient adaptation without accounting for adjustment costs, except in the agriculture and ecosystem sectors. Therefore, Tol may underestimate adaptation costs in some sectors of FUND. While climate change results in net global benefits at low temperature changes, higher temperature increases result in costs that adaptation cannot overcome as evidenced by the negative impacts of climate change on consumption by the late 21st century as predicted by FUND 3.6 (Tol, 2013).

Unlike Nordhaus and Tol, Hope (2011) explicitly models climate adaptation in PAGE09. Hope explicitly models adaptation and the cost of adaptation. For each non-catastrophic damage sector (sea level rise, market, and non-market), he specifies a temperature level up to which adaptation is 100 percent effective, a temperature level up to which adaptation is partially effective, and a level of effectiveness (the percentage of damages not incurred) for temperature increases between these two levels. For catastrophic damages, there is no adaptation. Like DICE and FUND, adaptation is not effective enough to significantly eliminate damages.

Given that included damages are significant despite current adaptation assumptions, adaptation as an argument for ignoring currently omitted damages is not justifiable. Furthermore, the three IAMs used by the IWG are often accused of being overly optimistic in their adaptation assumptions, particularly for the versions used by the 2010 IWG (Dietz et al., 2007; Ackerman, 2010; Warren et al., 2006; Hanemann, 2008; Ackerman et al., 2009; Masur and Posner, 2011). In particular, none of the three IAMs explicitly model mal-adaptation. Therefore, omitted damages are likely to still be significant, and current SCC estimates from DICE-2013, FUND 3.6, and PAGE09 are likely biased downward due to a tendency to be overly optimistic about adaptation (Masur and Posner, 2011).[122]

CONCLUSION – MOVING FORWARD

The IWG SCC estimates are likely biased downward due to the modeling decisions of EPA scientists and IAM developers, including the use of outdated damage estimates and the omission of a significant number of damage categories. While some of the damage estimates utilized by IAMs are outdated (Ackerman, 2010; Stern Review – Chapter 6; Stern, 2007; Dietz et al., 2007; Warren et al., 2006; Warren et al., 2010; Tol, 2009), updating these estimates is likely to have a minimal effect on the SCC (Yohe and Hope, 2013). Instead, this paper focuses on cataloging the more significant damages omitted from the recent versions of the three IAMs used by the Interagency Working Group (DICE-2010, FUND 3.8, and PAGE09), and the latest version of DICE (DICE-2013).[123] These omissions occur due to the omission of sectors (for example, socially contingent damages), the omission of relationships between regions and sectors (for example, inter-sector and inter-region damages), and the omission of types of climate damages from the underlying studies used for calibration (for example, fires).

The main question is whether the inclusion of these omitted damages matter. Tol (2009) argues that, for the most part, many omitted damages are small (saltwater intrusion in groundwater, increased cost of cooling power plants, adapting urban water management systems, storm frequency, intensity, and range, ocean acidification, and value of firewood),[124] and are balanced out by omitted climate benefits (decreased costs of some traditional and alternative energies—oil, wind, and wave, lower transport costs, lower expenditures on food and clothing due to lower demand from higher temperatures, and fewer transportation and other disruptions from cold-related weather).[125] For others, like tourism, the effects are unknown according to Tol (2009). Instead, Tol (2009) argues that research should primarily focus on estimating and including unknowns that potentially could have large effects, such as biodiversity loss, catastrophic damages, socially contingent damages, and damages at high temperature levels.[126] In other words, Tol (2009) argues that research should focus on tipping point damages and socially contingent damages; see row 3 and column 3 in Figure 2. Yohe and Tirpak (2007) for the most part agree with this assessment, but also include bounded risks (row 2 in Figure 2), which includes the effects of weather variability (droughts, floods, heat waves, and storms); the effects of weather variability are still greatly omitted from many of the included market and non-market damages. Furthermore, black swan events, that is, unexpected effects, related to climate change should further increase the SCC because researchers expect more negative than positive effects (Tol, 2009b). The inclusion of all omitted damages, including these more significant omitted damages, is likely to result in an increase in the SCC (Mastrandrea, 2009; Tol, 2009a). Given the difficulty of deciding *a priori* what damages are likely to be significant, this report advocates that IAMs should work to include all available damage estimates, particularly those discussed in this paper. However, priority for developing new damage estimates should be given to hot spots—regions and damages that are likely to be significant—for which estimates are not currently available.

There is a general consensus that future IAM research must focus on hot spots. The "hot spot" regions are those that are geographically predisposed to climate change (for example, low lying nations and island nations), and those nations with insufficient ability to adapt (for example, developing nations). The "hot spot" sectors are those discussed above: catastrophic damages, weather variability, and socially-contingent damages. While studying these sectors is difficult, analysts need to look at multiple metrics and regions. The current practice is to omit these difficult to estimate damages or to extrapolate damages estimates from developed to developing nations due to limited data availability. To overcome these shortcomings, future work will require the development of reliable datasets in developing nations and advancements in the science of climate variability and tipping points that specify credible scenarios at a regional level (Yohe and Tirpak, 2007). Furthermore, to develop consistent estimates of damages, the current pipeline of damage estimation, whereby scientists estimate potential damages and economists draw on these estimates in their studies independent of input from scientists, must be replaced with collaborative research between the disciplines.[127] This type of research ensures that economists understand the science behind the climate impacts that they are citing, but also ensures that the scientific estimates are developed with the final impact measurement, that is, the dollar impact, in mind.

Alternatively, further attempts to utilize meta-analysis at the aggregate scale (across regions and sectors) as is done in DICE-2013 are ill-advised.[128] There are several reasons to advise against this type of damage-function estimation. First, using meta-analysis makes determining which damages are included and excluded difficult. It requires an analyst to thoroughly study each of the underlying studies to determine which climate impacts on a sector are included and excluded. Furthermore, it is difficult to interpret whether an impact is included if only several studies include the impact. Second, there are too few data points at this scale to properly account for statistical issues: time trends, omitted damage sectors or impacts within sectors, and correlated standard errors between studies that include estimates from the same authors and similar estimation methods. Last, as discussed by Tol (2009), the data points from various studies are not really a time-series, and should not be treated as such. An alternative is to conduct meta-analyses at the sector level where a sufficient number of studies are available. For example, there are a multitude of agricultural studies, and a meta-analysis to estimate a regional-agricultural or global-agricultural damage function would be possible. Another alternative, laid out by Kopp, Hsiang, and Oppenheimer (2013) is to develop an infrastructure that uses statistical (for example, Bayesian) methods to update damage functions as new estimates become available.

Though not discussed in this paper, there are several additional compounding aspects of IAMs that are likely to further bias current SCC estimates downward. In particular, they fail to account for (1) uncertainty in extrapolating damages to higher temperatures given that IAMS assume only moderate temperature increases,[129] (2) a declining discount rate due to uncertainty over future economic growth (Arrow et al., 2013),[130] (3) aggregated and overly simplified spatial and temporal resolution (IWG 2010; Hanemann, 2008; Stern, 2007), and (4) the option value that arises from the irreversibility of CO_2 emissions. These shortcomings, by and large, point to a further bias downward of the social cost of carbon.

While there is a downward bias to the federal SCC estimates, this report advocates that the Office of Management and Budget (OMB) and other executive branch agencies should move forward to finalize proposed rules with the 2013 IWG's current SCC estimates, as measuring at least some of the costs is better than assuming there are none. In doing so, the OMB should emphasize more strongly the downward bias of the current U.S. SCC estimates and commit to addressing them in future updates of these estimates. Potentially, OMB can utilize the research provided in this report to list in detail all of the omitted damages in the current U.S. SCC estimates.

Table 1. 2010 and 2013 SCC Estimates at 3% Discount Rate by Model

IAM	2010 Global SCC at 3% Discount Rate (IWG 2010)	2020 Global SCC at 3% Discount Rate (IWG 2013)	% Change
DICE	$28	$38	34%
FUND	$6	$19	222%
PAGE	$30	$73	143%

Source: IWG (2013 Revision)

Table 2. 2010 SCC Estimates, 2010–2050 (in 2007 dollars per metric ton)

Discount Rate Year	5% Avg	3% Avg	2.5% Avg	3% 95th
2010	4.7	21.4	35.1	64.9
2015	5.7	23.8	38.4	72.8
2020	6.8	26.3	41.7	80.7
2025	8.2	29.6	45.9	90.4
2030	9.7	32.8	50.0	100.0
2035	11.2	36.0	54.2	109.7
2040	12.7	39.2	58.4	119.3
2045	14.2	42.1	61.7	127.8
2050	15.7	44.9	65.0	136.2

Source: IWG (2010)

Table 3. 2013 SCC Estimates, 2010–2050 (in 2007 dollars per metric ton)

Discount Rate Year	5% Avg	3% Avg	2.5% Avg	3% 95th
2010	11	32	51	89
2015	11	37	57	109
2020	12	43	64	128
2025	14	47	69	143
2030	16	52	75	159
2035	19	56	80	175
2040	21	61	86	191
2045	24	66	92	206
2050	26	71	97	220

Source: IWG (2010)

Table 4. Damage Studies and Income Elasticities Used to Estimate DICE-1999 Damage Function

Sector	Source of Damage Estimate (2.5 degrees Celsius)	Notes	Income Elasticity
Agriculture	Darwin et al (1995) and Dinar et al (1998)	Sub-regional impact estimates: Darwin et al (1995) and Dinar et al (1998); mainly uses Appendix Table B6 from Darwin et al (1995) assuming second most unfavorable GCM and land use is unrestricted.	0.1
Other Market Sectors	Author discretion	Unknown sources for sub-regional damage estimates. No damages to temperate climates based on Cline (1992), Nordhaus (1991), and Mendelsohn and Neumann (1999). Damages in non-temperature climates (cold, tropical, and semi-tropical) based on energy sector alone.	0.2
Coastal Vulnerability	Author discretion	Not directly based on one specific study, but highly influenced by Yohe and Schlesinger (1998); study omits storms, undeveloped land, and settlement so accounted for by author discretion.	0.2
Health	Murray and Lopez (1996)	Assign regional impacts based on the region from Murray and Lopez (1996) with which it most overlaps.	0
Non-market Impacts	Nordhaus (1998)	Use the Nordhaus (1998) estimate from climate-related time use in the U.S.; focusing mainly on increased outdoor recreation.	0
Human Settlement and ecosystems	Author discretion	Cite their own unpublished estimates of the capital value of climate sensitive human settlements and natural ecosystems in each sub-region, and estimate that each sub-region has an annual WTP of 1% of the capital value of the vulnerable system for a 2.5 degrees increase.	0.1
Catastrophic Climate Change*	Nordhaus (1994)	Assume 30% loss of global GDP for such an event and a rate of relative risk aversion of 4 for catastrophic risk. They use expert opinions of probabilities of a cataclysmic change drawn from Nordhaus (1994); the authors double the probabilities in the study for increasing concerns about these events for both 2.5 (measured at 3 degrees in study) and 6 degrees.	0.1

*Calibration sources are provided for 2.5 degrees of warming, but not 6 degrees of warming.
The one exception is catastrophic events.

Source: Nordhaus and Boyer (2000) and Warren et al (2006)

Table 5. Sector-Region Specific Damage Estimates for DICE-1999

	Non-catastrophic impacts						Catastrophic impact		TOTAL	
Subregion	Agriculture	Other vulnerable market	Coastal	Health	Non-market time use*	Settlements and ecosystems*	2.5 degrees Celsius	6 degrees Celsius	2.5 degrees Celsius	6 degrees Celsius
Africa	0.05%	0.09%	0.02%	3.00%	0.25%	0.10%	0.39%	2.68%	3.91%	-
China	-0.37%	0.13%	0.07%	0.09%	-0.26%	0.05%	0.52%	3.51%	0.22%	-
Eastern Europe	0.46%	0.00%	0.01%	0.02%	-0.36%	0.10%	0.47%	3.23%	0.71%	-
High Income OPEC	0.00%	0.91%	0.06%	0.23%	0.24%	0.05%	0.46%	3.14%	1.95%	-
India	1.08%	0.40%	0.09%	0.69%	0.30%	0.10%	2.27%	15.41%	4.93%	-
Japan	-0.46%	0.00%	0.56%	0.02%	-0.31%	0.25%	0.45%	3.04%	0.50%	-
Low Income	0.04%	0.46%	0.09%	0.66%	0.20%	0.10%	1.09%	7.44%	2.64%	-
Lower-middle Income	0.04%	0.29%	0.09%	0.32%	-0.04%	0.10%	1.01%	6.86%	1.81%	-
Middle Income	1.13%	0.41%	0.04%	0.32%	-0.04%	0.10%	0.47%	3.21%	2.44%	-
OECD Europe	0.49%	0.00%	0.60%	0.02%	-0.43%	0.25%	1.91%	13.00%	2.83%	-
Other High Income	-0.95%	-0.31%	0.16%	0.02%	-0.35%	0.10%	0.94%	6.39%	-0.39%	-
Russia	-0.69%	-0.37%	0.09%	0.02%	-0.75%	0.05%	0.99%	6.74%	-0.65%	-
United States	0.06%	0.00%	0.11%	0.02%	-0.28%	0.10%	0.44%	2.97%	0.45%	-
Global: 2100 GDP weights (i.e., 2.5 degrees Celsius)										
Output-weighted	0.13%	0.05%	0.32%	0.10%	-0.29%	0.17%	1.02%	6.94%	1.50%	8.23%

Source: Nordhaus and Boyer (2000) and Warren et al (2006)

Table 6. Sector-Region Specific Damage Estimates for DICE-2007

	Non-catastrophic impacts						Catastrophic impact		TOTAL	
	Agriculture	Other vulnerable market	Coastal	Health	Non-market time use*	Settlements and ecosystems*	2.5 degrees Celsius	6 degrees Celsius	2.5 degrees Celsius	6 degrees Celsius
United States	0.03%	0.00%	0.10%	0.02%	-0.28%	0.10%	0.94%	4.00%	0.91%	5.34%
European Union	0.03%	0.00%	0.46%	0.02%	-0.43%	0.25%	1.09%	4.80%	1.42%	9.06%
Add’l High Income	-0.05%	-0.32%	0.09%	0.02%	-0.35%	0.10%	1.11%	4.80%	0.61%	8.99%
Russia	-0.82%	-0.80%	0.05%	0.02%	-0.75%	0.05%	1.12%	4.80%	-1.13%	8.43%
Eurasia	0.03%	0.00%	0.01%	0.02%	-0.36%	0.10%	0.94%	4.00%	0.73%	4.76%
Japan	0.02%	0.00%	0.27%	0.02%	-0.31%	0.25%	1.07%	4.80%	1.31%	8.84%
China	0.02%	0.32%	0.08%	0.09%	-0.26%	0.05%	1.04%	4.00%	1.34%	7.92%
India	0.32%	0.29%	0.09%	0.40%	0.30%	0.10%	1.57%	6.00%	3.08%	12.94%
Middle East	0.35%	0.20%	0.04%	0.23%	0.24%	0.05%	0.96%	4.00%	2.08%	8.41%
Africa	0.67%	0.32%	0.02%	1.00%	0.25%	0.10%	1.78%	7.00%	4.13%	16.55%
Latin America	0.42%	0.28%	0.10%	0.32%	-0.04%	0.10%	1.30%	5.20%	2.48%	10.36%
Other Asia	0.52%	0.21%	0.09%	0.32%	-0.04%	0.10%	1.23%	5.00%	2.43%	10.00%
Global: 2105 weights (i.e. 2.5 degrees Celsius)										
Output weighted	-	-	-	-	-	-	1.16%	4.72%	1.77%	8.23%

Source: Nordhaus (2007)

Table 7. Damage Studies Used to Estimate the DICE-2013 Damage Function

Study	Temperature	Damage Estimate
Tol (2002)	1	-2.875
Rehdanz and Maddison (2005)	1	0.5
Hope (2006)	2.5	-1.125
Mendelsohn, Schlesinger, and Williams (2000)	2.5	0
Maddison (2003)	2.5	0.125
Nordhaus (2006)	2.5	1.125
Fankhauser (1995)	2.5	1.75
Nordhaus and Boyer (2000)	2.5	1.875
Nordhaus and Yang (1996)	2.5	2.125
Tol (1995)	2.5	2.375
Plambeck and Hope (1996)	2.5	3.125
Nordhaus (1994a)	3	1.625
Nordhaus (1994b)	3	6

Source: Tol (2009)

Table 8. PAGE 2002 Damage Function Parameters and Data Sources

Damage parameter	Mean	Min	Mode	Max	Source
Market Damages					
Econ impact in EU (%GDP for 2.5°C)	0.5	-0.1	0.6	1	IPCC (2001a, pp. 940, 943.)
Drop in econ impact OECD (%)	90				As in PAGE95a
Drop in econ impact RoW (%)	50				As in PAGE95a
Tolerable temp OECD economic (°C)	2				As in PAGE95a
Non-Market Damages					
Non-economic impact in EU (%GDP for 2.5°C)	0.73	0	0.7	1.5	IPCC (2001a, pp. 940, 943.)
Drop in non-econ impact (%)	25				As in PAGE95a
Market and Non-market					
Impact function exponent	1.76	1	1.3	3	As in PAGE95
Eastern Europe & FSU weights factor	-0.35	-1	-0.25	0.2	IPCC (2001a, p. 940.)
USA weights factor	0.25	0	0.25	0.5	IPCC (2001a, p. 940.)
China weights factor	0.2	0	0.1	0.5	IPCC (2001a, p. 940.)
India weights factor	2.5	1.5	2	4	IPCC (2001a, p. 940.)
Africa weights factor	1.83	1	1.5	3	IPCC (2001a, p. 940.)
Latin America weights factor	1.83	1	1.5	3	IPCC (2001a, p. 940.)
Other OECD weights factor	0.25	0	0.25	0.5	IPCC (2001a, p. 940.)
Tipping Point Damages					
Tolerable before discontinuity (°C)	5	2	5	8	IPCC (2001a, p. 952.)
Chance of discontinuity (% per °C)	10.33	1	10	20	
Loss if discontinuity occurs, EU (%GDP)	11.66	5	10	20	IPCC (2001a, p. 947.)

Source: Hope (2006)

Table 9. PAGE 2009 Damage Function Parameters and Data Sources

Damage parameter	Mean	Min	Mode	Max	Source
Sea Level Rise					
Initial Benefit (%GDP/°C)	0	0	0	0	-
Calibration sea level rise (m)	0.5	0.45	0.5	0.55	Anthoff et al., 2006
Sea level impact (% GDP)	1	0.5	1	1.5	Warren et al., 2006*
Sea level exponent	0.73	0.5	0.7	1	Anthoff et al., 2006
Market Damages					
Economic Initial benefits (%GDP/°C)	0.13	0	0.1	0.3	Tol, 2002
Econ impact in EU (%GDP for Cal. Temp.)	0.5	0.2	0.5	0.8	Warren et al., 2006*; IPCC AR4
Economic exponent	2.17	1.5	2	3	Ackerman et al, 2009
Non-Market Damages					
Non-economic Initial benefits (%GDP/°C)	0.08	0	0.05	0.2	Tol, 2002
Impact in EU (%GDP for Cal. Temp.)	0.53	0.1	0.5	1	Warren et al., 2006*; IPCC AR4
Non-economic exponent	2.17	1.5	2	3	Ackerman et al, 2009
Market and Non-market					
Calibration temperature (°C)	3	2.5	3	3.5	Warren et al., 2006*
Sea Level Rise, Market, and Non-market					
Impacts saturate beyond (% consumption)	33.33	20	30	50	Weitzman, 2009
US weights factor	0.8	0.6	0.8	1	Anthoff et al, 2006; Stern 2007, p143.**
OT weights factor	0.8	0.4	0.8	1.2	
EE weights factor	0.4	0.2	0.4	0.6	
CA weights factor	0.8	0.4	0.8	1.2	
IA weights factor	0.8	0.4	0.8	1.2	
AF weights factor	0.6	0.4	0.6	0.8	
LA weights factor	0.6	0.4	0.6	0.8	

Damage parameter	Mean	Min	Mode	Max	Source
Tipping Point Damages					
Tolerable before discontinuity (°C)	3	2	3	4	Lenton et al, 2008, table 1; Stern, 2007, box 1.4
Chance of discontinuity (% per °C)	20	10	20	30	Ackerman et al, 2009; Lenton et al, 2008, table 1; Stern, 2007, box 1.4
Loss if discontinuity occurs, EU (%GDP)	15	5	15	25	Anthoff et al, 2006 is the lower number; middle range is Nicholls et al, 2008, and the upper figure is Nordhaus, 1994.
Half-life of discontinuity	90	20	50	200	Hansen (2007) for short values; medium and long-run effects from Nicholls et al. (2008) and Lenton et al. (2008)

* Hope (2011) states that "They produce a mean impact before adaptation of just under 2% of GDP for a temperature rise of 3 °C (Warren et al, 2006), including the associated sea level rise of just under half a meter (Anthoff et al, 2006)."

Table 10. Taxonomy of Omitted Damages – Used in This Paper

Damage Category	Missing Damage Sector
Market Damages	Fisheries
	Pests, pathogens, and weeds
	Erosion
	Fire
	Energy Supply
	Transportation
	Communication
	Ecological dynamics
	Decreasing growth rate
Non-Market Damages	Recreational goods and services
	Ecosystem services*
	Biodiversity and habitat*
	Health care costs*
	Relative prices
Socially-Contingent Damages	Migration
	Social and political conflict
	Violence and crime
Catastrophic Damages	Tipping point*
	Fat tails
	Black swan events
Inter-Sector Damages	Inter-sector damages
Cross-Sector Damages	Inter-regional damages
	Destabilizers of existing non-climate stressors
	Weather variability and climate extremes
	Ocean acidification.

*Partially and/or insufficiently captured in current versions of DICE, FUND, and PAGE

Table 11. Alternative taxonomy of Omitted Damages

Damage Category	Damage sub-category	Missing Damage Sector
Missing Sector	Missing market and non-market sectors	Fisheries
		Energy Supply
		Transportation
		Communication
		Recreational goods and services
	Missing interactions	Inter-sector damages
		Inter-regional damages
	Poorly/incompletely estimated sectors	Biodiversity and habitat*
		Ecosystem services*
		Health care costs*
Missing Climate Effects	Broad system changes	Tipping point*
		Fat tails
		Black swan events
		Weather variability and climate extremes
		Ocean acidification
	Specific impacts from broad system changes	Ecological dynamics
		Pests, pathogens, and weeds
		Erosion
		Fire
	Missing dynamic climate effects	Decreasing growth rate
		Relative prices
		Socially contingent damage

*Partially and/or insufficiently captured in current versions of DICE, FUND, and PAGE

Table 12. Percentage Difference in Damages (with respect to European Damages) by Region and IAM (%)

	PAGE02	Mendelson et al (2000)	Nordhaus and Boyer (2000)	Tol (1999)	Tol's SE	Tol's Lower 95%	Tol's Upper 95%
US	25	-	17.86	91.89	-	-171.24	71.79
Europe	100	-	100	100	-	100	100
Japan/ Other OECD	25	-	17.86	27.03	-	188.89	39.39
Eastern Europe	-35	-	25 and -25	54.05	-	890.20	117.92
Middle East	-	-	-	29.73	-	524.84	67.55
Latin America	183	-	71.43	-2.70	-	208.50	13.43
South East Asia/India	250	-	175	-45.95	-	630.07	5.69
China	20	-	7.14	56.76	-	1258.17	148.53
Africa	183	-	139.29	-110.81	-	1374.51	2.65

Source: IPCC (2001)

Table 13. Damages by Region (as a % of GDP) and IAM

	PAGE02	Mendelson et al (2000)	Nordhaus and Boyer (2000)	Tol (1999)	Tol's Lower 95%	Tol's Upper 95%
US	-0.32	0.3	-0.5	3.4	1.048	5.752
Europe	-1.28	-	-2.8	3.7	-0.612	8.012
Japan/ Other OECD	-0.32	-0.1	-0.5	1	-1.156	3.156
Eastern Europe and Russia (FSU)	0.448	11.1	-0.7 and 0.7	2	-5.448	9.448
Middle East	0	-	0.7	1.1	-3.212	5.412
Latin America/Brazil	-2.3424	-1.4	-2	-0.1	-1.276	1.076
South East Asia/India	-3.2	-2	-4.9	-1.7	-3.856	0.456
China	-0.256	1.8	-0.2	2.1	-7.7	11.9
Africa	-2.3424	-	-3.9	-4.1	-8.412	0.212

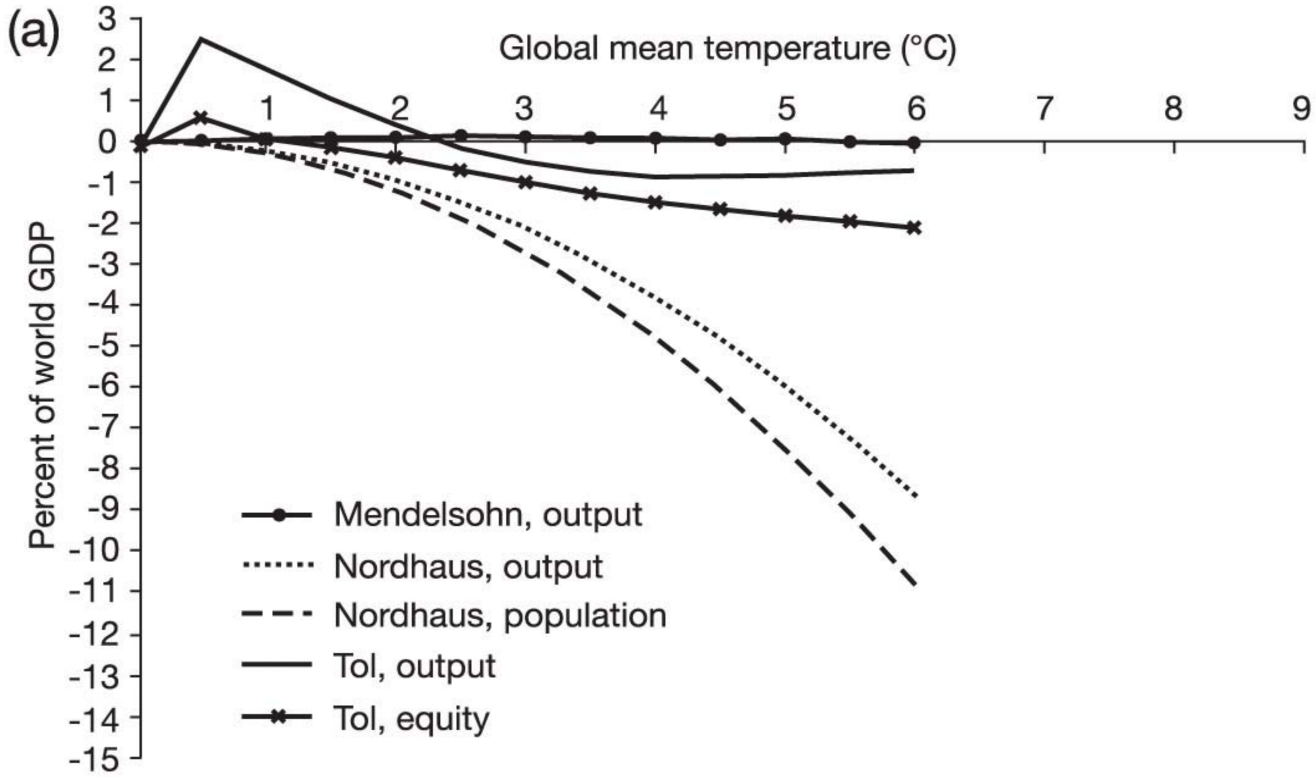
Source: IPCC (2001)

Table 14. Extreme Events

Phenomenon and direction of trend	Likelihood that trend occurred in late 20th century (typically post 1960)	Likelihood of a human contribution to observed trend	Likelihood of future trends based on projections for 21st century using SRES scenarios
Warmer and fewer cold days and nights over most land areas	Very likely	Likely	Virtually certain
Warmer and more frequent hot days and nights over most land areas	Very likely	Likely (nights)	Virtually certain
Warm spells/heat waves. Frequency increases over most land areas	Likely	More likely than not	Very likely
Heavy precipitation events. Frequency (or proportion of total rainfall from heavy falls) increases over most areas	Likely	More likely than not	Very likely
Area affected by droughts increases	Likely in many regions since 1970s	More likely than not	Likely
Intense tropical cyclone activity increases	Likely in some regions since 1970	More likely than not	Likely
Increased incidence of extreme high sea level (excludes tsunamis)	Likely	More likely than not	Likely

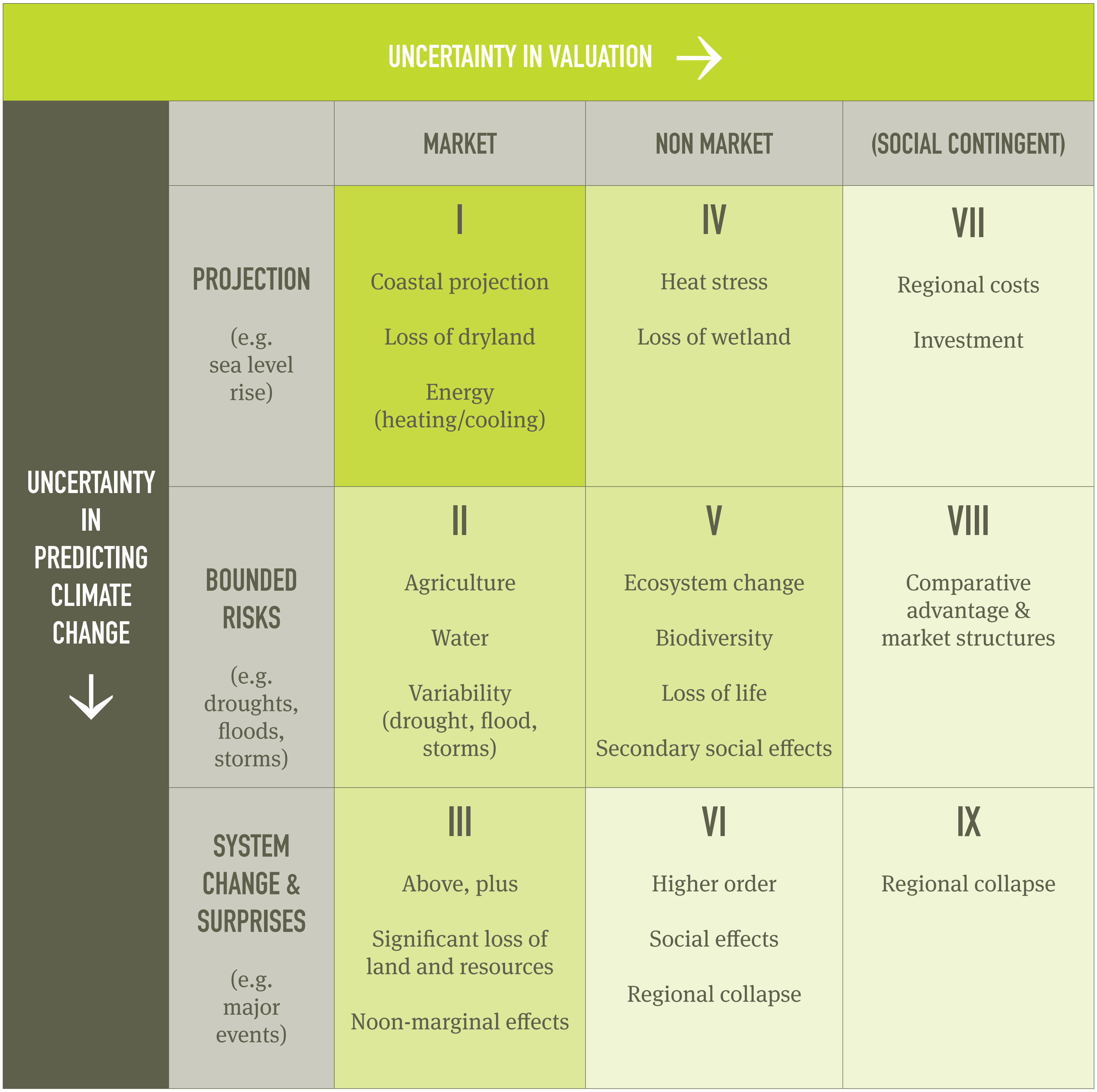
Source: IPCC (2007a) – Summary for Policymakers, Table SPM.2 on page 8

Figure 1. Damage Estimates as a % of Global GDP vs. Global Mean Temperature



Source: Figure 20.3a in IPCC (2007) and Figure 19.4 in IPCC (2001b)

Figure 2. Map of types of damages in IAMS by level of scientific and economic uncertainty



UNCERTAINTY IN VALUATION →

UNCERTAINTY IN PREDICTING CLIMATE CHANGE ↓

	MARKET	NON MARKET	(SOCIAL CONTINGENT)
PROJECTION (e.g. sea level rise)	I Coastal projection Loss of dryland Energy (heating/cooling)	IV Heat stress Loss of wetland	VII Regional costs Investment
BOUNDED RISKS (e.g. droughts, floods, storms)	II Agriculture Water Variability (drought, flood, storms)	V Ecosystem change Biodiversity Loss of life Secondary social effects	VIII Comparative advantage & market structures
SYSTEM CHANGE & SURPRISES (e.g. major events)	III Above, plus Significant loss of land and resources Noon-marginal effects	VI Higher order Social effects Regional collapse	IX Regional collapse

Source: Yohe and Tirpak (2007)

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NOTES

[1] In other words, the SCC is the marginal cost of carbon as measured by the present value of all future damages.

[2] This integration is necessary to capture the various steps of the climate process that translate an additional unit of carbon into a social welfare loss: economic and population growth emissions atmosphere concentrations temperature changes economic damages welfare loss.

[3] FUND 3.5 and FUND 3.8 were released in 2009 and 2012, respectively. At the time that this report was written, documentation for FUND was only available up until version 3.6. Since then, Tol released the documentation for version 3.7. Only small changes were made between versions 3.7 and 3.8 based upon peer reviewed science updates.

[4] The IWG provides four SCC estimates. Averaging SCC estimates across all IAMs and socio-economic scenarios (giving each equal weight), the updated estimates for the 2015 social cost of carbon are $11, $37, and $57 for discount rates of 5 percent, 3 percent, and 2.5 percent, respectively, and $109 for the 95th percentile SCC at a 3 percent discount rate averaged across all IAMs and scenarios.

[5] This includes maintaining assumptions about the climate sensitivity parameter, socio-economic and emissions scenarios, and discount rates used in 2010 estimates.

[6] While continued effort is necessary to update damage estimates currently included in IAMs, which often date back to the 1990s (Ackerman 2010; Dietz et al., 2007; Warren et al., 2006; Tol 2009), Yohe & Hope (2013) demonstrates, within the context of the PAGE model, that updates to market damage estimates (equivalent to a 10 percent increase or decrease) will only slightly affect the SCC. Instead, Yohe & Hope (2013) highlight non-economic (also known as non-market) damages, some of which are omitted from IAMs, as areas for more effective improvement (Yohe & Tirpak 2008). In other words, significant downward bias is more likely to result from omitted damages than from outdated damages.

[7] The three models we discuss in this report are not those used by the 2013 IWG. Similar to the 2013 IWG, we discuss PAGE09. Unlike the 2013 IWG, we also discuss DICE-2013 and FUND 3.6. The 2013 IWG utilized DICE-2010 in their calculations instead of DICE-2013. However, because DICE-1999 is utilized in the calibration of PAGE09 and the damage function in DICE-2010 is very similar to the damage function in DICE-1999, we implicitly discuss the omitted damages in DICE-2010. The 2013 IWG utilized FUND 3.8 in their calculations instead of FUND 3.6. However, at the time this report was researched, documentation for FUND was only available up until FUND 3.6. Tol only made minor changes between versions 3.6 and 3.8. For the purposes of this report, no additional damages were included by the author.

[8] Market damage estimates are generally based on either an enumerative approach or a statistical approach. The enumerative approach takes estimates of the physical impacts of climate change by sector (e.g., impact on crop yield or land lost through sea level rise) and then applies economic indicators (e.g., market crop prices or coastal land values) to estimate damages. Specifically, analysts combine physical impact studies from the sciences with prices from economic studies to determine damage estimates, and then, because many of these damage studies are region and sector (e.g., agriculture, forestry, etc.) specific in nature, utilize benefit transfer and aggregation methods to produce a global damage estimate. The statistical approach estimates welfare changes by observing variations in prices and expenditures across space under varying climate conditions. Specifically, analysts estimate climate damages using econometric techniques based on current observations of the climate and economic variables (income, budget shares, and happiness measurements). Enumerative studies have been criticized for ignoring overlaps and interactions between sectors. Statistical surveys draw criticism for overlooking important, non-climate regional differentiators such as structural institutions and for excluding damages that vary temporally but not spatially (i.e., sea level rise and catastrophic impacts). In other words, both estimation methods rely heavily on extrapolation (Goulder & Pizer, 2006; Tol, 2009; Brouwer & Spaninks, 1999).

[9] For example, in the United States, climate-related increases in morbidity and mortality comprise 6 percent to 9 percent of the decrease in GDP but 13 percent to 16 percent of the decrease in household welfare (Jorgenson et al., 2004).

[10] While the transition point from climate benefits to climate damages in Tol (2009) is incorrect in magnitude due to a sign error in the citation of the damage estimate from PAGE02 (Hope 2006) and several other citation errors, the general result of positive net benefits from climate change will likely still hold for low temperature increases after their correction. However, the transition point is likely to occur at a lower temperature threshold.

[11] While Nordhaus assumes no initial benefits from climate change in DICE-2007 and DICE-2013, he allows for initial benefits in DICE-1999 and DICE-2010; Nordhaus estimates net global benefits from climate change up until a 1.29°C increase in global surface temperature in DICE-1999, and no initial benefits in DICE-2010. Hope explicitly models initial benefits in PAGE09, but does not in PAGE02; only Eastern Europe and the former Soviet Union experience climate benefits in PAGE02, which is captured implicitly through a negative damage weighting factor. In PAGE09, Hope includes an additional term in the market and non-market damage functions to account for climate benefits for low temperature increases above pre-industrial levels. This allows for the possibility of positive benefits from climate change, though the exact threshold depends on the parameters drawn; see discussion below. In FUND 2.0, Tol (2002a) finds a net global benefit from climate change equivalent to 2.3 percent of GDP for a one degree Celsius increase; the resulting threshold is less clear.

[12] Because prices are not directly associated with non-market goods as they are with market commodities, a range of alternative valuation methodologies estimating preferences can be used. The value methodologies are traditionally grouped into revealed and stated preference techniques. Revealed preference techniques use market goods to estimate the value of environmental or safety amenities embedded in their prices (e.g., property value variations as a function of parks or pollution levels associated with different homes). In other words, these revealed preference methodologies assume that the price of market goods (e.g., property values) reflect the value of the ecological services or that, ceteris paribus, people will pay more to travel to places with greater ecological value. The usefulness of revealed preference methods in assessing non-market damages is limited because most non-market impacts do not induce price or quantity changes; this is particularly true for the valuation of species, habitat, and ecosystem services. Stated preference methods use interviews or surveys asking participants to identify either the price they would pay for a given ecological commodity, or the amount of a non-market commodity they would demand at a given monetary amount. While stated preference methods can be utilized to assess the willingness to pay (WTP) for non-market goods (Tol 2009; Smith et al., 2003), they have other limitations. In particular, answers depend on question wording, ordering effects, and practical or cognitive limitations in putting dollar values on intangible goods. They may also suffer from information limitations, depending on the good being valued.

With respect to environmental non-market goods, Boyd & Krupnick (2009) and others have compared ecological and economic production systems, arguing that valuation of ecosystem services implies a valuation of their respective outputs. These "outputs" (e.g., reduced flood risk, flourishing fish populations) can be reliably understood and valued by the public in ways that specific ecosystem services (e.g., nutrient cycling) cannot. Because an individual values the endpoint and not the process itself, when asked to value a specific ecosystem service, an individual will base his WTP for the service on his WTP for the "output" of that service. Stated preference valuation that focuses on the value of specific services (instead of outputs) often prove inaccurate because those surveyed assume ecological production factors that may not be consistent with each other or with reality (Boyd & Krupnick 2009).

[13] In other words, tipping points are generally more common in systems with intricate, codependent processes that when altered by exogenous conditions result in the failure of beneficial negative feedback loops or the propagation of detrimental positive feedback loops.

[14] Using a similar set of tipping elements, Nordhaus (2013) identifies four global tipping points: (1) collapse of large ice sheets, (2) large-scale change in ocean circulation, (3) feedback processes that trigger more warming, and (4) enhanced warming over the long-run.

[15] Anthoff and Tol (2013a) claim that FUND implicitly captures catastrophic damages. Specifically, catastrophic impacts arise by modeling the uncertainty of 900 parameters in the FUND model.

[16] More formally, Weitzman (2009) defines a probability distribution function as having fat tails "when its moment generating function (MGF) is infinite—that is, the tail probability approaches 0 more slowly than exponentially." Conversely, he defines a thin-tailed distribution as one characterized by "a [probability distribution function] whose [moment generating function] is finite." Nordhaus (2012) defines a fat-tail distribution as a distribution that follows a power law, which is a "distribution in which the probability is proportional to a value to a power or an exponent."

[17] For clarification purposes, medium-tailed distributions are sometimes referred to as thin-tailed distributions. This paper follows the convention laid out in Nordhaus (2012).

[18] Weitzman (2011) states that the "recipe" for fat tails is "deep structural uncertainty about the unknown unknowns of what might go very wrong … coupled with essentially unlimited downside liability on possible planetary damages." In other words "the operation of taking 'expectations of expectations' or 'probability distributions of probability distributions' spreads apart and fattens the tails of the reduced-form compounded posterior-predictive PDF (Weitzman 2009)."

[19] Weitzman argues that existing IAMs underestimate the decrease in welfare-equivalent output for extremely high changes in global temperature. The DICE-2010 model, for example, predicts that a 10°C increase in the mean global temperature would result in a 19 percent loss in global welfare equivalent output. Weitzman contends that for very large increases in global temperature damage functions lose much of their predictive ability as complications in spatial and temporal averaging as well as a priori conjecture compound (Weitzman 2011). This implies that there is considerable uncertainty over climate damages at high temperature levels.

[20] Using the value of civilization, Weitzman (2009) calculates a lower bound on consumption (i.e., survival level of consumption), and demonstrates that it is decreasing in the value of civilization.

[21] Citing Yohe & Tirpak (2008) and Tol (2008), Mastrandrea (2009) states that "while there certainly may be unassessed positive impacts from climate change, such summaries suggest that they are likely to be outweighed by unassessed negative impacts."

[22] The choice of functional form determines how climate damages are projected to higher temperatures and does not determine which damages are accounted for and which are omitted.

[23] IAM damage functions are usually calibrated with one point estimate (i.e., at one temperature level), though DICE-1999 is calibrated with two point estimates (i.e., at two temperature levels). In both cases, the lack of damage estimates from climate change at high temperatures makes results unreliable at high temperature (Kopp & Mignone 2012). On the one hand, if analysts use a point estimate (i.e., damage estimates at a particular temperature increase) to calibrate damage functions, the functional form determines damages at high future temperatures. However, without estimates at higher temperatures, analysts cannot determine the correct functional form (Kopp & Mignone 2012). On the other hand, if analysts use multiple point estimates, analysts must extrapolate low temperature damage estimates to high temperatures; this requires a multitude of assumptions, as in DICE-1999, making damage estimates at high temperature unreliable. There are several alternatives. One alternative, utilized by Ackerman & Stanton (2012), is to assume that climate damages reach 100 percent of GDP at a particular temperature level based on the Weitzman argument that humans cannot live at 12 degrees Celsius higher. Another alternative, utilized by Hope (2006; 2011), is to conduct sensitivity analysis over the calibration temperature and damage value.

[24] FUND calibrates sector damage functions to a one degree Celsius increase in temperature. Unlike DICE and PAGE, which assume that climate damages are power functions of temperature increases, Tol assumes sector-specific equations of motion (equations that specify how damages evolve over time based on how physical systems, emissions, income, and population underlying these damages change over time) to extrapolate damage estimates to higher temperatures (and time periods). These equations rely on various assumptions about physical and economic processes, and rely heavily on parameter calibration.

[25] In terms of author discretion, all three IAMs rely heavily on author discretion. However, this reliance has declined with newer versions of the models.

[26] In addition to the default versions of these IAMs, various other versions of these models exist in publication where analysts (including the original developers) modify the default versions to capture differing growth paths or other potential variations.

[27] Whether the damage functions have a linear term, which allows for initial benefits from climate change, in addition to the quadratic term, depends on the version of the model. Only DICE-1999 and DICE-2010 include these linear terms, while Nordhaus sets this parameter equal to zero in DICE-2007 and DICE-2013.

[28] The regions in the DICE-1999 model are: United States, China, Japan, OECD Europe, Russia, India, other high income, high-income OPEC, Eastern Europe, middle income, lower middle income, Africa, and low income.

[29] Because the DICE-1999 climate damages are a function of temperature and temperature squared, two data points are necessary to calibrate the damage equation: damage estimates at 2.5 degrees and 6 degrees Celsius. Damage estimates for a 2.5 degree Celsius increase are available in the literature. Due to unavailability of damage estimates at 6 degrees, damage estimates at 2.5 degrees Celsius are extrapolated to 6 degrees Celsius.

[30] Nordhaus makes several updates to the damage estimates because some regions had climate benefits for high temperatures and catastrophic damages could have been calibrated more carefully in DICE-2000. First, Nordhaus calibrates the damage function using agricultural damage estimates drawn from "Cline's agricultural studies." However, it is unclear which of Cline's papers were used. Second, he no longer accounts for risk aversion when calculating catastrophic damages. This adjustment lowers catastrophic damage estimates. Third, Nordhaus utilizes updated regional GDP estimates to aggregate regional damage estimates to the global scale. In addition, Nordhaus drops the linear term from the quadratic

damage function (Nordhaus, 2008). Fourth, though not mentioned in Nordhaus (2008), Nordhaus does not extrapolate damages from low levels to high levels as discussed in Nordhaus and Boyer (2000); this is possible because Nordhaus eliminates the linear temperature term in the damage function. Last, Nordhaus changes the regions in the model to: the United States, Western Europe/European Economic Zone, Other-High Income, Russia, Eastern Europe/Former Soviet Union, Japan, China, India, Middle Eastern, Sub-Saharan Africa, Latin America, and Other Asian. See Table 6 for DICE-2007 region-sector specific damage estimates.

[31] Anthoff and Tol (2013a) states that "FUND does not assume that there is a probability of disastrous impacts of climate change. Rather, we vary all parameters randomly and it so happens that particular realizations are catastrophic."

[32] Again, this discussion refers to the default version of PAGE09.

[33] According to Hope (2006), in PAGE02, the economic and non-economic damage estimates for 2.5 degree Celsius increase in temperature is based on pages 940 and 943 of the IPCC (2001a) and the tipping point damages are based on pages 947 and 952 of the IPCC (2001a). The combined market and non-market damage estimates on page 940, i.e., Table 19-4, include Pearce et al. (1996), Tol (1999), Mendelsohn et al., (2000), and Nordhaus and Boyer (2000), and the estimates on page 943, i.e., Figure 19-4, include Tol (2002a), Mendelsohn & Schlesinger (1997), and Nordhaus & Boyer (2000). Because the IPCC (2001a) cites only global damage estimates for Pearce et al., (1996) in Table 19-4 and it does not include estimates for Pearce et al., (1996) in Figure 19-4, it is likely that Hope (2006) does not base his regional damage estimates on this source. Similarly, because the IPCC(2001a) does not cite European climate damage estimates for Mendelsohn et al., (2000) in Table 19-4 and cites different estimates from Mendelsohn, i.e., Mendelsohn & Schlesinger (1997), in Figure 19-4 , it is again likely that Hope (2006) does not base his damages estimates on this source. Furthermore, the damage estimate of a 1.23 percent decline in GDP (with a range of -0.1 percent to 2.5 percent) used in PAGE2002 for Europe for a 2.5 degree Celsius increase in temperature do not match the damage estimates from Tol (1999) of a 3.7 percent increase in GDP for Europe with a standard deviation of 2.2 percent and a -2.8 percent decline in European GDP from a 2.5 degree Celsius increase in temperature; see Tables 10 and 11. Instead the damage estimates are closer to the Nordhaus & Boyer (2000) damage estimates. However, the Hope (2006) damage estimates do not replace Nordhaus & Boyer (2000). Similarly, it is unclear what source Hope (2006) uses to breakdown damage estimates between his market and non-market sectors. The market and non-market damage estimates, including their distribution parameters and breakdown between the two sectors, are best described as based on author's judgment informed by Nordhaus & Boyer (2000), Tol (1999), and Tol (2002a).

[34] In Page2002, only Eastern Europe could potentially reap climate benefits from temperature increases.

[35] For market damages, this temperature threshold increases with adaptation.

[36] Hope (2006) calibrates his discontinuous damage function parameters based on discussions in the IPCC (2001a) on pages 947 and 952. Specifically, Hope (2006) calibrates the parameters corresponding to the percentage GDP loss in Europe for a discontinuity and the tolerable temperature risk using general statements about discontinuous damages in the IPCC (2001a). This implies that Hope (2006) utilized his discretion to calibrate the discontinuous damage function parameters.

[37] See footnote 12 for a discussion of revealed and stated preference.

[38] Ecosystem services and secondary social effects (such migration) are for the most part excluded from IAMs.

[39] Note that FUND implicitly accounts for catastrophic damages; see footnotes 15 and 31. As a consequence, FUND may implicitly capture market and non-market catastrophic damages to the extent that the assumed probability distribution functions for uncertain parameters capture tipping points.

[40] With respect to FUND 3.6, Tol (2013) explicitly states: "Some impacts are missing altogether – air quality, violent conflict, labour productivity, tourism, and recreation. Weather variability is poorly accounted for, and potential changes in weather variability ignored. The model assumes that there are few barriers to adaptation. There are no interactions between the impact sectors, and therefore are no higher order effects on markets or development."

[41] Ocean acidification, wildfires, and pests, pathogens, and weeds affect the market sector via agriculture, forestry, and or fisheries and the non-market sector via biodiversity, ecosystem services, human health, and/or human settlements.

[42] In many of the enumerative studies that do include fisheries, fisheries are abstractly captured under "other market" damages.

[43] See footnote 8 for a discussion of the enumerative and statistical approaches to estimating climate damages.

[44] Given the uncertainty of the effect of climate change on fisheries, Sumaila et al., (2011) argues that fisherman may increase their current fishing efforts given the possibility of lower future fishing stocks.

[45] Phytoplankton are essential to the ocean food web and the global climate system. In terms of the latter, "Marine phytoplankton are responsible for [approximately] 50 percent of the CO2 that is fixed annually worldwide (Toseland et al., 2013)."

[46] For example, ozone emissions from fuels lower crop yields (Ackerman and Stanton 2011).

[47] Ozone impacts are counted separately in BCA analysis as traditional pollutants, not caused by climate change.

[48] The CO_2 fertilization effect in FUND 3.6 is drawn from studies that assume a fertilization effect based on enclosure experiments, as do the studies behind DICE-2013 that account for this effect. However, DICE-1999, and therefore to some extent PAGE09, and several of the other studies behind DICE-2013 exclude the CO_2 fertilization effect altogether.

[49] As discussed in Koetse and Rietveld (2009), some research casts doubt on the possibility of the Northwest Passage being a valid future shipping route.

[50] Due to lower water levels, substantial increases of inland water-way transportation costs are possible. High water levels due to heavy precipitation events can also result in river closures (Koetse and Rietveld, 2009).

[51] Network effects are delays, detours, and cancellations due to disruptions in the transportation network. In other words, transportation costs may be incurred in areas not directly affected by an extreme event due the propagation of costs throughout the network. These costs may be substantial (Koetse and Rietveld, 2009).

[52] Bigano et al. (2007) state that "world aggregate expenditures hardly change, first rising slightly and then falling slightly." However, there is a considerable noise in the resulting estimates.

[53] As noted, DICE-2013 uses a combination of enumerative and statistical studies. While the statistical studies may capture some dynamic effects indirectly, all of these studies are cross-sectional in nature.

[54] As a consequence, Moyer et al., (2013) argues that DICE assumes a weak propagation of damages on growth.

[55] The modified version of DICE used by the IWG eliminates the potential effect of climate change on economic growth through how it models changes in the savings rate.

[56] The intuition is that mitigation spending in the present is equivalent to asking the current generation earning approximately $50,000 per household to transfer money to a future generation in 2300 earning $1.5 million per household (Moyer et al., 2013).

[57] This point is made by Dasgupta (2006) with respect to Nordhaus' DICE model. "Despite the serious threats to the global economy posed by climate change, little should be done to reduce carbon emissions … [Norhduas'] idea is not that climate change shouldn't be taken seriously, but that it would be more equitable (and efficient) to invest in physical and human capital now, so as to build up the productive base of economies (including, especially, poor countries), and divert funds to meet the problems of climate change at a later year. These conclusions are reached on the basis of an explicit assumption that global GDP per capita will continue to grow over the next 100 years and more even under business as usual, an assumption that the [Stern] Review would appear to make as well." Given that the Stern Review utilized PAGE02, Dasgupta is in a sense making this point about PAGE as well.

[58] According Hope, it is possible in PAGE09 for climate change damages to be large enough to negatively affect consumption growth, such that the discount rate becomes negative (personal correspondence with Hope, 2014).

[59] While the Dell, Jones, & Olken (2012) estimate relies on annual data rather than medium-run or long-run average of temperature and precipitation, the authors do provide medium-run estimates that compare average growth rates between 1979 and 1985 and from 1985 to2000. In these medium-run cases, they again find negative effects of higher temperatures on the growth rates of poor nations.

[60] Butkiewicz and Yanikkaya (2005) do find that the costs of social-political instability increase the higher the level of national income and democracy of a nation.

[61] Higher temperatures require workers to take more breaks, work fewer hours, and/or decrease work intensity (i.e., slow down) (Kjellstrom et al., 2009).

[62] While not discussed here, it is possible that as vector-borne diseases spread, more countries could become mired in poverty-disease traps, such as in current sub-Saharan Africa (Fankhauser and Tol, 2005).

[63] "The impacts on labor supply are non-trivial. If temperatures were to rise by 5 degrees Celsius in the United States by the end of the coming century and no adaptation occurs, U.S. labor supply would fall by roughly 0.6 hours per week in high-exposure industries, representing a 1.7 percent decrease in hours worked and thus earnings. In developing countries, where industrial composition is generally skewed toward climate-exposed industries and prevailing temperatures are already hotter than those in most of the United States, the economic impacts are likely to be much larger (Zivin & Neidell, 2010)."

[64] Modeling such changes in DICE may be difficult. On the one hand, Hall & Behl (2006) argue that "with irregular flickering between climate states, characteristic of past climatic transitions, we would expect the destruction of capital stock. If the flickering is forced by human activity, then policy or lack thereof results in the destruction of capital stock and a discontinuity of the rate of return on capital, violating the equilibrium condition." On the other hand, computer general equilibrium models, including ICES and ENVISAGE, have no such problem. ICES and ENVISAGE do not model capital losses as shocks, but instead use expected losses (Bosello et al., 2012; Roson & van der Mensbrugghe, 2010).

[65] The simplicity of the Cass-Koopmans model is particularly useful for making generalizations about the impact of climate change on factor productivity and economic growth. However, this simplicity also ignores certain empirical realities of economic growth (Lecocq & Shalizi, 2007). For example, the Cass-Koopmans model assumes a single aggregate good, while economies consist of multiple industries that are possibility affected differently by climate change. In another example, the Cass-Koopmans model assumes a production function with constant returns to scale, whereas, an economy characterized by increasing returns to scale may become "trapped" at a low growth rate if climate change causes large and frequent shocks to capital or labor productivity or stocks (Aziadaris & Stachurski, 2005).

[66] In DICE, it could be argued that declines in labor and capital productivity are already captured by their expression for "climate damages as fraction of output."

[67] Both the health and labor productivity damage sectors are effects on labor productivity. However, health effects are loss of labor productivity due to a decrease in labor stock through death and inability to work from disease, while the labor productivity damage sector accounts for decline in "on-the job" performance due to humidity and high temperatures.

[68] Like ENVISAGE, the authors of ICES model health damage as an effect on labor productivity.

[69] Environmental goods and services will become relatively scarcer than market goods and services due to climate change and other anthropomorphic drivers. As explained later in this subsection, because current damage estimates are estimated using willingness to pay estimates derived from data from the current time period, they fail to account for the future increases in the value of environmental goods relative to market goods due to the law of scarcity. By adopting structural modeling assumptions that also imply constant relative prices (i.e., that the relative value of non-market to market goods is constant over time), the developers of IAMs bias the SCC downward.

[70] Another example is disease regulation services, which are captured via health damage functions.

[71] Another example is air quality regulation, which is partially captured in PAGE09 via the DICE-1999 damage function. DICE-1999 captures the health effects of air pollution, which is omitted from FUND altogether. DICE-2013 mostly likely omits this damage because Nordhaus and Boyer (2000) is only one of 13 studies utilized to calibrate its damage function.

[72] Another example includes ecosystem services related to biochemicals, natural medicines, and pharmaceuticals.

[73] Another example is climate amenities, which includes cultural services, such as aesthetics, and outdoor leisure activities (i.e., non-market time use). Only earlier versions of DICE (i.e., DICE-1999 and DICE-2007) explicitly attempt to capture these services via Nordhaus' estimate of non-market amenities. However, DICE-1999 only captures outdoor leisure activities, and omits all cultural values. However, even these estimates have come under considerable fire from Hanemann (1998) and Ackerman (2010).

[74] The assessment of damages on ecosystem services depends on a valuation of those services based on public WTP. Boyd and Krupnick (2009) and others have compared ecological and economic production systems, arguing that valuation of ecosystem services implies a valuation of their respective outputs. These "outputs" (e.g., reduced flood risk, flourishing fish populations) can be reliably understood and valued by the public in ways that specific ecosystem services (e.g., nutrient cycling) cannot. Because an individual values the endpoint and not the process itself, when asked to value a specific ecosystem service, an individual will base his WTP for the service on his WTP for the "output" of that service. Stated preference valuation that focuses on the value of specific services (instead of outputs) often prove inaccurate because those surveyed assume ecological production factors that may not be consistent with each other or with reality (Boyd & Krupnick, 2009).

[75] One such improvement could be to value the final outputs of species. In addition to their aesthetic and non-use values, analysis could estimate the value of the genetic material of species, an ecosystem service discussed in the previous subsection.

[76] In addition to his own criticism of how FUND values biodiversity, the model has also come under criticism by other economists. They argue that assuming that biodiversity loss is a function of temperature change, instead of temperature level, is incorrect because it implies ecosystem adaptation to climate change (Warren et al., 2006). As a consequence, ecosystem damages decline in the long run as temperature increases level off (Warren et al., 2006).

[77] This aggregate consumption good, often referred to as a numéraire, equals the combined economic values of all market and non-market goods divided by the global population.

[78] Constant relative prices imply that a decline in the supply of a consumption good (market or non-market) does not affect its price relative to all other goods and services. If the relative price of the good were to increase in response to this decline in supply, there would be no demand for the good because consumers could obtain more utility (i.e., welfare) by switching their expenditure to all other goods and services (due to the perfectly substitutable assumption). This would put downward pressure on the good's price until it reached its original value relative to all other prices.

[79] Discussions about changing relative prices date back to earlier literatures. Neumayer (1999) calls this argument the Krutilla-Fisher rationale from Krutilla and Fisher (1975). In the context of manufactured and public goods, Baumol (1967) describes a similar phenomenon called Baumol's disease. The discussion of changing relative prices also has roots in the earlier literatures of weak sustainability and strong sustainability.

[80] In this context, the elasticity of substitution measures the ease at which market goods can be substituted for non-market goods. An elasticity of substitution less than one implies that market goods and non-market goods are complements in the long run. In the extreme, perfect complements are when market goods cannot be substituted at any level to make up for the loss of non-market goods. An example would be subsistent water levels, where no amount of a market good can replace its value. An elasticity greater than one implies that market goods and non-market goods are substitutes (Heal, 2009). In the extreme, perfect substitutes are when market goods can be substituted at a constant rate to make up for a loss of non-market goods, regardless of the level of non-market goods available.

[81] In the language of sustainability, an elasticity less than one implies strong sustainability in the long run. An elasticity greater than one implies weak sustainability in the long run.

[82] It should be unsurprising that the discount rate requires updating because growth rates of man-made and environmental goods and services differ. In addition, the rationale for discounting, i.e., that the future will be better off due to continued economic growth, is weakened with the elimination of the perfect substitutability assumption.

[83] For example, the results can also apply to agricultural and non-agricultural goods. Heal (2009) argues that food shortages could result in the relative value of agricultural goods increasing from its currently insignificant level in most developed nations.

[84] Initially, Sterner and Persson (2008) assume that elasticity of substitution is equal to 0.5, 10 percent of current utility comes from non-market goods, and that 50 percent of damages are attributable to non-market goods. The remaining parameters follow the standard assumptions of DICE.

[85] The utility function chosen in Sterner and Persson (2008) assumes a constant elasticity of substitution, and implies only that a positive level of environmental services is essential (i.e., not zero).

[86] A small example of the possible magnitude of these relocation costs are Alaskan native villages. In the case of relocating three villages (Kivalina, Shishmaref, & Newtok), the cost is estimated by the U.S. Army Corps of Engineers to be between $275 million and $455 million. While these costs are high, they should be interpreted as an upper bound on costs due to the remoteness of these villages (Lynn & Donoghue, 2011).

[87] A decline in income may also decrease the opportunity cost of engaging in violence and civil conflict (Dell, Jones, & Olken, 2013).

[88] There is an argument in the literature that higher temperatures and extreme weather may not actually cause conflict, but actually just shifts future conflicts to the period of higher temperatures or more extreme weather. Hsiang, Meng, and Crane (2011) demonstrate that climate change will actually cause "new" conflicts, rather than just shifting the time periods of "existing" conflicts.

[89] While the studies vary in their focus over time and space, all 60 studies rely on the same general panel or time-series model. Cross-sectional studies and studies that control for confounding factors are avoided because these confounding factors are potential avenues through which climate can affect conflict. These 60 studies utilize 45 different conflict datasets. Two-thirds of these studies have been published since 2009.

[90] The number of inter-personal conflicts far exceeds inter-group conflicts. Thus, a smaller percentage increase in inter-personal conflicts than inter-group conflicts can result in a far greater increase in the number of inter-personal conflicts than inter-group conflicts.

[91] Violence on an individual scale, such as increased aggression in the police force, can result in more inter-group conflict. Thus, these two types of conflicts are correlated, such that an increase in interpersonal violence can increase the possibility of intergroup conflict.

[92] These 60 studies find that: an increase in temperature raises violent crime faster than it increases property crime; increases in precipitation increase personal and intergroup violence in poorer, agricultural-dependent communities; low and high temperatures and low water availability lead to organized political conflicts; windstorms and floods affect the level of civil conflicts; institutional breakdowns occur in developing economies when they become sufficiently climate stressed.

[93] These mechanisms include: decreased supply of resources leads to disagreements over their allocation; climate change makes conflict more appealing with regards to achieving a stated objective; declines in labor productivity make conflict relatively more desirable; declining state capacity reduces the ability of government institutions to suppress crime and provides incentives for competitors to increase the conflict; increased pressure for a redistribution of assets because of increased social and income inequality; increases in food prices; increasing migration and urbanization leading to conflict over geographically stationary non-climate related resources; changes in the logistics of human conflict increases incentives for conflict; a physiological response with respect to cognition, attribution, and/or aggression resulting from higher temperatures increases human propensity for conflict.

[94] Certainty equivalent catastrophic damages are the guaranteed magnitude of catastrophic climate damages that humanity finds equally desirable as (that is, is indifferent to) risky (that is, the unknown magnitude of) catastrophic damages that we currently face. Due to humanity's general aversion to risk, humans are willing to pay a premium to avoid risk.

[95] In DICE-2013, Nordhaus excluded damages from tipping points. Only two out of the 13 studies used include catastrophic damages. One of these studies, Hope (2006), does so at temperatures above the temperature used to calibrate the DICE-2013 damage function, that is, 2.5 degrees Celsius. As a consequence, the meta-analysis really only includes one study that accounts for tipping points. To rectify this shortcoming and *other omitted damages*, Nordhaus and Sztorc (2013) refit the damage curve after multiplying the damage estimates in Tol (2009) by 1.25. Specifically, Nordhaus and Sztorc (2013) state that "current studies generally omit several important factors (the economic value of losses from biodiversity, ocean acidification, and political reactions), extreme events (sea level rise, changes in ocean circulation, and accelerated climate change), impacts that are inherently difficult to model (catastrophic events and very long-term warming), and uncertainty (of virtually all components from economic growth to damages)." Comparing the unadjusted and adjusted damage estimates (that is, estimates that do not and do assume a 25 percent increase in damages, respectively), Nordhaus and Sztorc (2013) implicitly assume omitted damages of 0.34 percent of GDP at 2.5 degree Celsius and 1.94 percent of GDP at 6 degree Celsius. In contrast, catastrophic damages in DICE-1999 are 1.02 percent at 2.5 degrees Celsius and 6.94 percent degrees Celsius according to Nordhaus and Boyer (2000), while they are 1.16 percent at 2.5 degrees Celsius and 4.72 percent at 6 degrees Celsius in DICE-2007; DICE-2010 makes the same assumption as DICE-2007. To achieve the levels of catastrophic damages observed in DICE-1999, Nordhaus and Sztorc (2013) would have used an adjustment of between 77 percent and 91 percent. Similarly, to achieve the catastrophic damages observed in DICE-2007, the authors would need to have chosen an adjustment of between 62 percent and 87 percent. Therefore, if we believe that the certainty equivalent measure of catastrophic damages is anywhere near the scale proposed in these earlier versions of DICE, the 25 percent increase by Nordhaus is nowhere near sufficient to account for the potential cost of tipping points in the climate system, let alone the *other omitted damages*.

[96] Nordhaus and Sztorc (2013), which is the source code for the default version of DICE-2013, specifies that the damage function is

where is the percentage loss in GDP from climate tipping points and T is the global average surface temperature. However, the tipping point damage is turned off in the default version, implying that it is excluded in the catastrophic damage function. In Nordhaus (2013), the tipping-point damage function in his recent book (Chapter 18 – footnote 5) is

This appears to only be used in a very limited analysis, and Nordhaus (2013) states that this damage function is "at the outer limit of what seems plausible and have no solid basis in empirical estimates of damages, so that should be interpreted as illustrating how tipping points might affect the analysis."

[97] The first scenario could be driven by the accelerated increase in atmospheric GHG concentrations driven by the release of greenhouse gas stocks or by the reduced albedo (i.e., the reflectivity of the Earth's surface) due to melting ice sheets. In either case, the rate of radiative forcing per unit of CO_2 is greater. The second tipping-point scenario is motivated by increased GHG atmospheric longevity due to the degradation of carbon sinks (e.g., forests, algae, and agricultural crops). Climate-driven dieback of trees in boreal and tropical forests or algae deaths would reduce Earth's capacity to sequester carbon, effectively increasing the amount of time carbon lingers in the atmosphere by decreasing the decay rate of atmospheric carbon. More persistent carbon would then place carbon sinks under increased pressure, presumably decreasing the decay rate further.

[98] Anthoff and Tol (2013a) states that "FUND does not assume that there is a probability of disastrous impacts of climate change. Rather, we vary all parameters randomly and it so happens that particular realizations are catastrophic."

[99] "A Monte Carlo simulation will run an integrated assessment model thousands of times, each time randomly picking the value of uncertain parameters from a probability distribution function, i.e., a function that assigns a probability to each possible parameter value. For example, the Working Group ran 10,000 Monte Carlo simulations for each of the three IAMs and five socio-economic scenarios, randomizing the value of climate sensitivity, i.e., the change in average global temperature associated with a doubling of CO_2, and all other uncertain parameters in the IAMs by the original authors. For each randomly drawn set of values, the IAM estimated the associated damages, with the final SCC estimate equaling the average value across all 10,000 runs, five socio-economic scenarios, and then across all three models. Therefore, each SCC estimate is calculated using 150,000 runs (EDF, NRDC, Policy Integrity, and UCS comments, 2013)."

[100] These distributions, according to Anthoff and Tol (2013a), "are occasionally derived from meta-analyses of published estimates, but more often based on 'expert guesses'."

[101] Specifically, Anthoff and Tol (2013a) state that "the fat tails found in the Monte Carlo analyses in FUND are a result, rather than an assumption."

[102] Pycroft et al., (2011) uses similar definitions of thin, medium, and fat tails as discussed earlier. To summarize, Pycroft et al., (2011) state that "thin-tailed probabilities, declining exponentially or faster; fat-tailed probabilities, declining polynomially or slower; intermediate-tailed probabilities, declining slower than exponentially but faster than polynomially."

[103] Considering only the change in the climate-sensitivity parameter distribution from the default assumption in PAGE09 (i.e., the triangular distribution) to the three modified distributions, the PAGE09 SCC estimate increases from $102 to $131 (thin), $146 (medium), and $188 (fat); even larger percentage increases are observed for the 95th and 99th percentile SCC estimates. After accounting for a decline in the PAGE09 SCC estimate from $102 to $76 from turning off the catastrophic damage function, the SCC increases from $76 to $99 (thin), $94 (medium), and $114 (fat) when considering only changes in the distributions of the damage function exponents.

[104] See footnote 8 for a discussion of the enumerative and statistical approaches to estimating climate damages.

[105] Yohe and Hope (2013) emphasize this concern. They warn that "to beware of analyses that are so narrow that they miss a good deal of the important economic ramifications of the full suite of manifestations of climate change; i.e., that they miss interactions in the climate system that allow climate change, itself, to be a source of multiple stress even within one particular sector."

[106] Tol (2009) states that "In the enumerative studies, effects are usually assessed independently of one another, even if there is an obvious overlap—for example, losses in water resources and losses in agriculture may actually represent the same loss."

[107] See footnote 8 for a discussion of the enumerative and statistical approaches to estimating climate damages.

[108] In the statistical approach, analysts estimate climate damages using econometric techniques. While there are several identification strategies, which differ in method and types of climate damages captured, all econometric methods rely on current observations of the climate to estimate future climate damages.

[109] While trade is not a positive spillover per se, it is an inter-regional benefit that is only captured through the modeling of connections between regions.

[110] Tradable goods represent only a fraction of market goods. They do not include market services, non-market goods and services, or market goods with prohibitively high transportation costs.

[111] Tol (2009) states: "In Bosello, Roson, and Tol (2007) and Darwin and Tol (2001), my coauthors and I show that sea level rise would change production and consumption in countries that are not directly affected, primarily through the food market (as agriculture is affected most by sea level rise through land loss and saltwater intrusion) and the capital market (as sea walls are expensive to build). Ignoring the general equilibrium effects probably leads to only a small negative bias in the global welfare loss, but differences in regional welfare losses are much greater."

[112] Technology spillovers between nations do not guarantee that the worldwide cost of mitigation and adaptation will decrease.

[113] In FUND 3.6, the number of migrants from the loss of dry land is equal to the product of land loss and average population density. The number of migrants between two regions is assumed to be a constant proportion of the overall number of migrants from the origin (sending) region: migrants from developed regions (United States, Canada, Western Europe, Japan and South Korea, Australia and New Zealand, Central and Eastern Europe, and the former Soviet Union) all resettle within their region of origin; 90 percent of migrants from developing regions (Middle East, Central America, South America, South Asia, Southeast Asia, China plus other nearby nations, North Africa, and sub-Saharan Africa) resettle within their region of origin, and the remaining 10 percent of migrants emigrate to developed regions; migrants from small island nations resettle in other regions: developed and developing (Anthoff and Tol, 2010).

[114] Cline (1992) cites data showing that state and local government spending in 1989 was approximately $3,000 per capita and assumes that immigrants do not pay taxes for their first 18 months in the United States and subsequently cover their share in state and local government expenditures. This yields an estimated cost per migrant of $4,500, which was approximately 25 percent of U.S. per capita income in 1990; a 40 percent cost per migrant, as assumed by FUND, however, would correspond to a $7,200 cost per migrant in the U.S. scenario. The average non-agricultural wage in the United States was $17,994 in 1990 (Economic Report of the President, February 1991, 336 from Cline, 1992). The 40 percent figure likely comes from Fankhauser (1995; 50), who cites Cline (1992) in assuming that global warming will increase immigration by 17 percent worldwide; this figure from Cline (1992), however, was simply an illustration of the cost of migration to the United States and was hardly a "guesstimate," as stated by Fankhauser. Further, Fankhauser applies the $4,500 cost per migrant from Cline (1992) to estimate cost of migration to OECD countries, and follows Ayres and Walter (1991) in assuming a $1,000 cost per migrant to non-OECD regions (Fankhauser, 1995; 51). The latter figure is based on foregone output a person would have produced had he or she not migrated. These assumptions are used to estimate a global cost of migration of $4.33 billion (Fankhauser, 1995; 50), which is likely the source of the estimated cost of migration used in FUND.

[115] See http://www.economist.com/news/europe/21590946-bulgaria-struggling-cope-syrian-refugees-nightmare-all.

[116] See http://www.bbc.co.uk/news/world-23813975.

[117] Freeman and Guzman (2009) state that "In addition to ecological changes, several of the other factors which contribute to the emergence of new diseases will very likely be exacerbated by global warming, including migration (as noted above) and breakdowns in public health infrastructures. It is impossible to say with certainty that climate change will result in new diseases—such emergences are highly complex, multi-factored developments—but it is very clear that climate change will substantially increase this risk."

[118] The United Nations' Millennium Ecosystem Assessment states that "The loss of species and genetic diversity decreases the resilience of ecosystems, which is the level of disturbance that an ecosystem can undergo structure or functioning. In addition, growing pressures from drivers such as overharvesting, climate change, invasive species, and nutrient loading push ecosystems toward thresholds that they might otherwise not encounter. ... The most important direct drivers of change in ecosystems are habitat change (land use change and physical modification of rivers or water withdrawal from rivers), overexploitation, invasive alien species, pollution, and climate change."

[119] There are many threats to future water supplies other than climate change. First, many regions in the United States are currently overpumping their ground water (http://ga.water.usgs.gov/edu/gwdepletion.html), In developing nations, water withdrawals are expected to increase over the next 50 years (Millennium Ecosystem Assessment). Furthermore, water pollution and increased water demand due to a growing population are also issues.

[120] Given that gross revenue of marine captured fisheries (i.e., excluding aquaculture) equals approximately $80 billion to $85 billion annually globally (Sumaila et al., 2011), the effect on U.S. shellfish is small.

[121] For example, the agricultural damage estimates used by Nordhaus include the benefits of farmer adaptation to climate change; see forthcoming Appendix A.

[122] The adaptation assumptions underlying PAGE09 are more conservative than PAGE02. As a consequence, this downward bias is likely less significant for PAGE, as it is for the other two IAMs (Hope, 2006; Hope, 2011).

[123] This paper uses FUND 3.6 instead of FUND 3.8 as mentioned earlier; at the time this report was researched, documentation for FUND was only available up until FUND 3.6. Tol only made minor changes between versions 3.6 and 3.8. For the purposes of this report, no additional damages were included by the author.

[124] DICE-1999 and FUND 3.6, and PAGE09 as a consequence of being greatly informed by these two IAMs, exclude the value of firewood. The studies underlying the forestry damage estimates, i.e., Perez-Garcia et al., 1997; Sohngen et al., 2001, focus on industrial products manufactured from wood, but do not consider the use of wood for fuel. Perez-Garcia et al. (1997) note that fuel uses of wood accounted for roughly half of all timber harvests at the time of the study. Additionally, non-timber aspects of forests (e.g., recreation, water, wildlife, etc.) are only considered to the extent that they are captured in other sectors.

[125] It should be noted, however, that some of these categories also have damages associated with them that are omitted, such as increased energy supply costs due to increased weather variability and extreme events.

[126] Tol (2009) believes that unless a fundamental shift in the literature occurs, improving estimates of willingness to pay for biodiversity and ecosystem services will not affect the SCC. Citing Pearce and Moran (1994), he states that individuals are limited in their willingness to pay for conservation.

[127] This argument is based on statements by David Anthoff at the Cost-Benefit Analysis and Issue Advocacy Workshop on October 28, 2013 at New York University School of Law.

[128] This type of analysis does not represent new data or methodologies as discussed in the previous paragraph.

[129] Only DICE and FUND fail to account for the uncertainty in the functional form of damage equation.

[130] By utilizing the Ramsey discount rate equation, the three IAMs allow for declining discount rates resulting from declining economic growth rates. However, the 2010 and 2013 IWG estimates impose an external assumption of constant discount rates.

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