An Initial Estimate of the Cost of Lost Climate Regulation Services Due to Changes in the Arctic Cryosphere

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1. Introduction

Many people are familiar with the recent graphic images of shrinking ice on the Arctic Ocean, and may be aware of projections that the Arctic could be ice-free in the summer by the year 2030. However, there is little recognition of the significant loss in *economic value* that the disappearance of Arctic sea ice, snow, glaciers and permafrost could impose on humans.

The frozen Arctic may seem to visitors to be simply a barren sea- and landscape, but in fact it serves as habitat for many species and is the foundation for the Inuit and other indigenous cultures of the North. Arctic sea ice has anchored the ecosystems of northern regions and helped regulate global climate for at least 800,000 years (Overpeck et al., 2005). Its seasonal disappearance would have far-reaching ecological, climatic, and economic impacts that we are just beginning to understand.

On a global scale, the reflective surfaces of ice and snow have a cooling effect. Sea ice formation and melting help drive the world's ocean currents, permafrost traps vast quantities of methane and other forms of carbon, and the Greenland Ice Sheet holds enough water to raise sea level by 7 meters (AMAP, 2009). Greenland is in fact losing ice and contributing to sea level rise at a much faster rate than scientists predicted only a few years ago (Mernild et al., 2009).

This paper will provide an overview of selected global ecosystem services provided by the Arctic cryosphere in the form of climate regulation. We will focus on three components that were chosen because observations and modeling results are consistent and provide a relatively clear picture of what has happened and what is most likely in store for the remainder of the 21st century. We also provide initial estimates of the economic value of the contributions to global climate regulation that could be lost due to Arctic warming. These quantitative estimates are provided for the year 2010, and cumulatively through the years 2050 and 2100.

The three effects that we quantify are changes in sea and land albedo (reflectivity) and changes in methane emissions. As sea ice and snow-cover melt, they reveal darker surfaces that absorb more heat. Scientists have estimated the amount of methane release that results from thawing of permafrost (ground that has remained below the freezing point for two or more consecutive years). We convert the additional planetary warming caused by these three effects into annual CO_2 equivalents, and then calculate the costs incurred by that additional warming using various estimates of the per ton social cost of carbon estimates. Other components and global effects of the cryosphere have not been addressed here due to greater complexity, with the result that our estimates of costs are likely to be partial and may be an underestimate of the full costs of loss of the frozen Arctic.

We estimate that on an annual basis in 2010, albedo changes from loss of sea ice and snow cover, along with accelerating methane emissions, are heating the planet at a rate equivalent to approximately 3 billion metric tons of CO_2. This is comparable to about 42 percent of US global warming emissions. This heating from the melting Arctic will grow significantly over the coming decades, projected to more than double by 2100 when expressed in CO_2 equivalents.

In economic terms, estimated costs in 2010 from the decline in albedo and increase in methane emissions range from $61 billion to $371 billion. By 2050, this number rises to a cumulative range of $2.4 trillion to $24.1 trillion. Over the remainder of the century, cumulative costs to society could range from $4.9 trillion to $91.2 trillion. The large range of the estimate reflects: uncertainty associated with the planet's temperature sensitivity to increased carbon emissions (climate sensitivity); uncertainty associated with the actual future impacts from a given increase in temperature; uncertainty associated with total emissions levels, economic growth and population growth over the coming decades; and, especially, the choice of discount rate.

This paper provides initial estimates of only one of the ecosystem services provided by the northern cryosphere, global climate regulation. It serves as a scoping exercise pointing to additional work that needs to be carried out. In particular, we recognize the value that the frozen Arctic has for the people who live there and the range of ecosystem services that the Arctic environment provides for them. We do not attempt here to describe or quantify those values and services, in part because a way of life cannot be captured in monetary value and in part simply to emphasize an often-overlooked aspect of the frozen Arctic: the services that it provides to the Earth's climate system. If protecting the climate function of the frozen Arctic also means preserving the habitat and homeland of Arctic peoples and their environment, then humans benefit doubly. Conversely, if the frozen Arctic disappears, climate services are only one part of what will be lost to humanity and the Earth.

The paper is organized as follows: section 2 provides a qualitative overview of the climate related ecosystem services provided by the frozen arctic; section 3 generates estimates of the additional climate forcing, converted to CO_2 equivalents, produced by changing snow and ice albedo, and by methane releases due to thawing and degradation of permafrost in the tundra and boreal ecosystems; section 4 reviews the literature on the social cost of carbon; section 5 derives estimates for the economic value of lost climate regulation services caused by the warming Arctic; and section 6 concludes.

2. Climate Regulation and the Cryosphere

The surface air temperature over the Arctic region is increasing at a rate about twice that of the rest of the world (Polyakov et al., 2002; Serreze and Francis, 2006). This warming is already influencing the Arctic ecosystems and the humans that depend on them, and is expected to continue throughout the remainder of the 21st century (ACIA, 2005). The greater rate of warming in the Arctic is due to the large number of positive feedback mechanisms in the region. A positive feedback results when the reaction to an initial stimulus amplifies the effect of that stimulus. A negative feedback occurs when the reaction to a stimulus dampens the effect of the initial stimulus. Currently, in the Arctic, the positive feedback mechanisms are stronger than the negative feedback mechanisms.

One of the better known feedback mechanisms is the snow and ice albedo feedback loop. In the Arctic, this loop is strong since the surface is generally bright due to the ice and snow. As snow or ice melts, a darker surface is exposed, less solar energy is reflected back to space, and more energy is absorbed. This absorbed energy then heats the atmosphere, resulting in further temperature increases, melting, and temperature increases again. Another strong positive feedback loop in the Arctic is related to the methane release from the thawing of permafrost. Rising air temperatures cause increases in emissions of methane from permafrost soils, which in turn raise atmospheric greenhouse gas concentrations, leading to a further increase in temperature. Accurately quantifying these feedback loops and their interactions is challenging, but as warming continues, it is likely that these feedbacks will intensify. This section first reviews the major positive feedbacks impacting climate regulation that are driven by Arctic warming, and then turns to quantitative forecasts of these effects for the remainder of the 21st century.

Decreasing Albedo from Sea Ice. The extent of the summer sea ice has declined since the beginning of the record in 1953, with the lowest value recorded in 2007, the second lowest in 2008, and the third lowest in 2009 (Stroeve et al., 2007; NSIDC, 2010). In addition, there is a strong thinning of multiyear ice and an increase in the area of melt ponds (Maslanik et al., 2007). All of these factors exacerbate the ice-albedo positive feedback loop to warming (Light et al., 2008; Pedersen et al., 2009). Research suggests that if the current rate of decline of the summer sea ice extent continues, then the Arctic Ocean may become seasonally ice-free by the middle of the 21st century, or possibly earlier (Holland et al., 2006). A winter ice cover will likely persist for centuries. The amplified warming caused by the loss of summer sea ice is not constrained to the Arctic Ocean, but is also expected to influence adjacent land areas, especially during autumn and winter, and may lead to hastened degradation of certain types of permafrost (Lawrence et al., 2008).

Decreasing Albedo from Snow Cover. Currently, the snow cover in the Arctic is present for about 200 days per year. A decrease in the duration of the snow season under a warming climate results in a positive feedback mechanism and increased warming. Across the Pan-Arctic between 1970 and 2000, there was a decrease in duration of the snow season of approximately 2.5 days per decade. This translates into a 2.5 W m^{-2} (Watts per square meter) per decade increase in absorbed energy across the pan-Arctic during this same period for the snow-free season (Euskirchen et al., 2007). Model projections indicate that by the end of the 21st century, the annual number of days with snow cover in the Arctic will decrease by approximately 44 days from the current duration of 200 days.

Increasing Methane Emissions from Thawing of Permafrost. The behavior of the Arctic methane cycle through the remainder of the 21st century is highly uncertain. Methane is present in the atmosphere in much smaller concentrations than carbon dioxide, but it is a more potent greenhouse gas with a high global warming potential.

Over a 100-year time scale, methane is 25 times more effective per molecule than CO_2 at absorbing long-wave radiation, which means that it has 25 times the warming potential of CO_2. Research suggests that methane emissions have outweighed methane consumption in the Arctic (McGuire et al., 2009). These methane emissions in the Arctic come primarily from wet soils, where methane-producing bacteria dominate. Therefore, large increases in methane emissions may occur if permafrost thaw increases dramatically, leaving a water-logged landscape. Some of the uncertainty in projections of methane releases stems from the possibility that permafrost thaw will lead to a drier landscape due to increased drainage, which would reduce methane emissions. Currently, however, the Arctic terrestrial land surface is a net source of methane at 41.5 Tg (teragrams = megatons) CH_4 per year, increasing by 0.5 Tg CH_4 per year between 1997 and 2006 (McGuire et al., In Review) in conjunction with changes in soil temperature and soil moisture.

Other Global Climate Processes and Impacts. In addition to these three processes, there are several other mechanisms by which the frozen Arctic affects global climate. Sea level will rise as the Greenland Ice Sheet loses mass, a process that is already underway and may be accelerating (AMAP, 2009). This effect is captured in the estimates of the social cost of carbon dioxide emissions discussed below. Other changes are harder to model and have thus been left out of this initial analysis. Ocean currents may shift as sea ice disappears and a driving force in global ocean circulation—sea ice formation and melt in the northern North Atlantic—is altered. Arctic continental shelves hold vast quantities of methane hydrates, and the release of methane from these hydrates could cause additional global warming.

Another potential source of greenhouse gases is carbon dioxide in the Arctic, but aggregate changes in the Arctic carbon cycle through the 21st century are unclear. The Arctic at present is a global sink of CO_2; from 1997 to 2006 the terrestrial region of the Arctic gained 51 Tg C per year as CO_2 while the Arctic Ocean gained 57.8 Tg C per year as CO_2 (McGuire et al., In Review). The Arctic Ocean may become a stronger sink in coming decades, but the terrestrial environment appears to be getting weaker in this regard. In the ocean, additional uptake of CO2 will continue the trend in ocean acidification, with negative consequences for marine organisms in contrast to any global benefits from slowing the buildup of atmospheric CO_2. Undoubtedly there are further effects that humans will only discover if and when they occur. For a full accounting of the costs of a melting Arctic, further research is needed to analyze existing observations, design new monitoring techniques, and model future trajectories of these and other changes, as well as their physical, biological, and economic impacts.

3. Calculation of the Forcing from Albedo Changes and Methane Releases

We calculated added global forcing in emissions of CO_2 equivalents (CO_2e) due to changes in Arctic sea ice, snow cover, and methane emissions for the period 2010 to 2100. We used a number of different literature sources and model estimates to inform these calculations. Not all steps in the conversions to CO_2e have been done before and some uncertainty remains. We note where we have made assumptions and simplifications for the purpose of this initial estimate. We calculated two emissions scenarios, a lower end and a higher end, with the lower end representing less climate warming than the higher-end scenario. We describe these emissions calculations below.

Sea-Ice Albedo Feedback. As noted above, the effect of the disappearance of summer sea ice is a projected amplification of climate warming due to the sea-ice albedo feedback loop. To determine the change in forcing due to the loss of summer sea ice, we used the results of sensitivity tests in a modeling study that showed that 20 to 40 percent of the 4 W m^{-2} increase in temperature in response to forcing from doubled CO_2 (~690 ppm by 2100) is due to sea ice loss (Rind et al., 1995; Bony et al., 2006). This globally averaged temperature response translates to roughly a 4 W m^{-2} adjustment to the top of the atmosphere forcing by 2100. That is, by 2100, sea ice loss is expected to exert 0.8–1.6 W m^{-2} on the top of the atmosphere radiation budget due to the resulting darker surface that absorbs more heat.

We calculated the forcing values for the years from 2010–2100 by adjusting the forcing values to expected CO_2 concentration values (and by extension, the expected warming) for that given year. For example, say in 2040 that the expected CO_2 concentration is 500 ppm. Under the warming scenario where the 690 ppm represents a doubling of CO_2 and the heating due to the loss of sea ice in 2100 is 0.8 W m^{-2}, then the warming under 500 ppm is 0.8*(500/690) = 0.57 W m^{-2} warming for the year 2040. Our scenario assumes all the summer sea ice disappears in August of each summer by the year 2050, so that albedo losses stop at this point, and forcing does not increase further (see Figure 1). We make two simplifying assumptions for this calculation. The first is that CO_2 increases are linear, although it is more likely that these increases will be nonlinear. The second assumption is that the adjustments to the forcing are instantaneous, when in reality the 0.8–1.6 W m^{-2} adjustment may not be realized until years later. From an economic standpoint, this would have the effect of delaying the cost, although the cost would still eventually occur.

We translated this warming in W m^{-2} into CO_2 equivalents through the year 2100 (when the doubling of CO_2 has occurred) based on the methodology outlined in Zhuang et al. (2006) and Euskirchen et al. (In Press). Briefly, the goal of this conversion was to approximate the amount of carbon sequestration or release that is equivalent to a 1 W m^{-2} cooling or heating effect. We assumed that globally a 4.0 W m^{-2} atmospheric heating change is caused by a doubling of atmospheric CO_2. At 350 ppm CO_2 there is roughly 700 Pg C storage, corresponding to 1,400 Pg C storage at 700 ppm, taking into account the fertilization effect of increased atmospheric CO_2 on terrestrial and marine ecosystems. Dividing the increase in carbon in grams (700 Pg C = $700*10^{15}$ g C) by the surface area of the globe (5.10×10^{14} m^2) yields 1372 g C m^{-2} increase for a doubling of CO_2. Then, dividing 1372 g C m^{-2} by 4.0 W m^{-2} resulted in a 343 g C m^{-2} increase/decrease in carbon sequestration for a 1 W m^{-2} cooling/heating effect. We then converted the 343 g C m^{-2} into CO_2 equivalents by multiplying by 3.67 to get 1259 CO_2e per m^{-2}.

Snow-Cover Albedo Feedback. Across the Pan-Arctic between 1970 and 2000, a decrease in duration of approximately 2.5 days per decade of the snow season translates to a 2.5 W m^{-2} per decade warming across the pan-Arctic during this same period (Euskirchen et al., 2007). In the future, under scenarios of climate change, this decrease in snow cover duration is expected to accelerate, with a 4.4 days per decade decrease in Alaska, or a 44 day decrease in the length of the snow season by 2100 for a middle-of-the-road climate scenario. This translates into an increase in atmospheric heating of 4.3 W m^{-2} per decade across the pan-Arctic (Euskirchen et al., 2009).

The snow-cover albedo feedback calculations take into account the different albedo values between tundra and the various forest types across the pan-Arctic (broadleaf, evergreen needleleaf, deciduous needleleaf) during both snow-free and snow-covered periods. These calculations do not take into account forest disturbance and forest regrowth due to such factors as fire or insect damage. Note that the land surface following fire has a higher albedo (translating into more heat reflected back to space), which is a negative feedback to climate warming. However, since the heightened fire regime also causes a positive feedback due to the reduced forest carbon uptake and large carbon emissions, this negative feedback is almost balanced out by the positive feedbacks (Randerson et al., 2006).

The estimates we present here increase by half a percent per year for a lower-end scenario, and by one percent per year for a higher-end scenario in correspondence with lower-end and higher-end climate warming scenarios. These estimates of changes in heating are translated into CO_2 equivalents based on the methodology in Zhuang et al. (2006) and Euskirchen et al. (In Press) summarized above.

Feedbacks Due to Methane Emissions from Thawing Permafrost. Predicting the feedbacks to warming due to the release of methane in the Arctic under permafrost degradation is complicated by a large number of factors. These factors include: whether a land surface becomes wetter or drier under permafrost thaw; future changes in fire regimes; thermokarst (physical depressions of the ground surface) distribution; and interactions between temperature and soil moisture. Between 1997 and 2006 the Arctic terrestrial land surface was a net source of methane at 41.5 Tg CH_4 per year on average, increasing by 0.5 Tg CH_4 per year between 1997 and 2006 in conjunction with changes in soil temperature and soil moisture (McGuire et al., In Review). Studies of future changes in methane in Alaska estimate that the rate of increase will be 1.0 Tg CH_4 per year (Zhuang et al., 2004 and 2006). Therefore, for the estimates presented here, we use the lower end of 0.5 Tg CH_4 per year for the lower end of emissions, and the higher 1.0 Tg CH_4 per year for the higher end of emissions. The figures for 2100 are consistent with, and somewhat lower than, estimates reported in Anthony (2009).[1]

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[1] Anthony estimates that in the year 2100 the range of methane emissions due to thawing permafrost will likely be between 2.5 and 5 billion metric tons CO_2e. Our estimates for the year 2100 are somewhat lower, 2.2 to 3.4 billion tons. Anthony's estimate, over the century, is that methane emissions alone will drive an increase in global temperatures of 0.32°C.

Figures 1-4 chart the upper and lower estimates for CO_2e impacts over the century due to each of the three factors analyzed here—sea-ice albedo declines, snow-cover albedo declines, and methane increases from thawing permafrost—as well as their combined impacts.

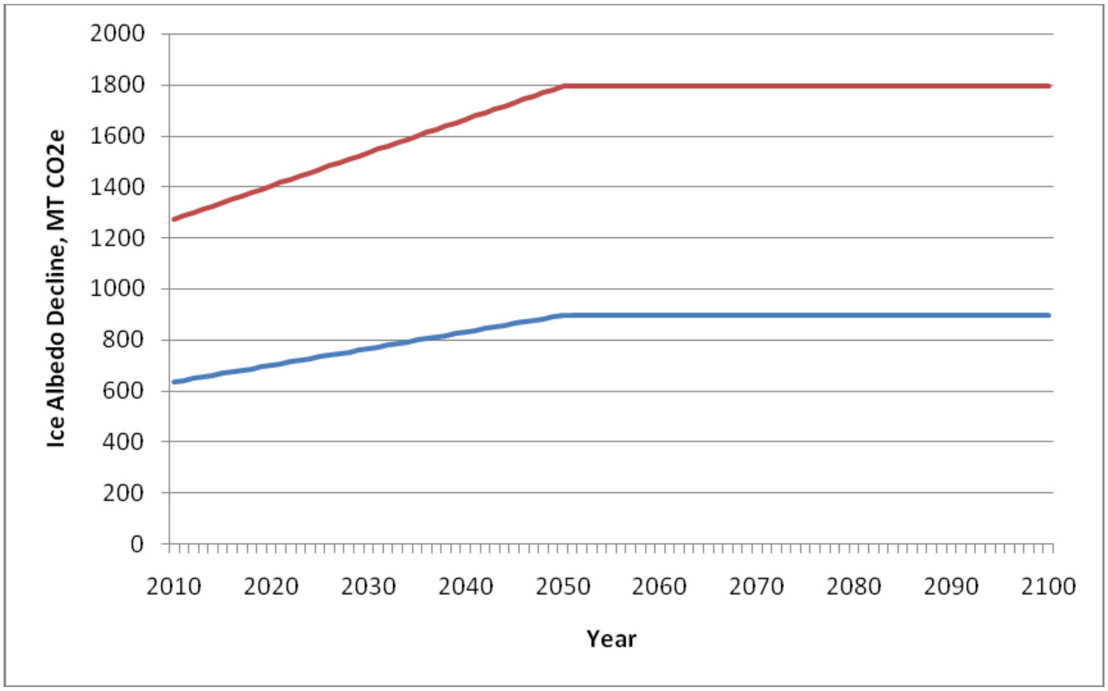

Figure 1. Range of Potential Annual Forcing Due to Sea-Ice Albedo Declines (2010 to 2100), in MT (million metric tons) of CO_2e.

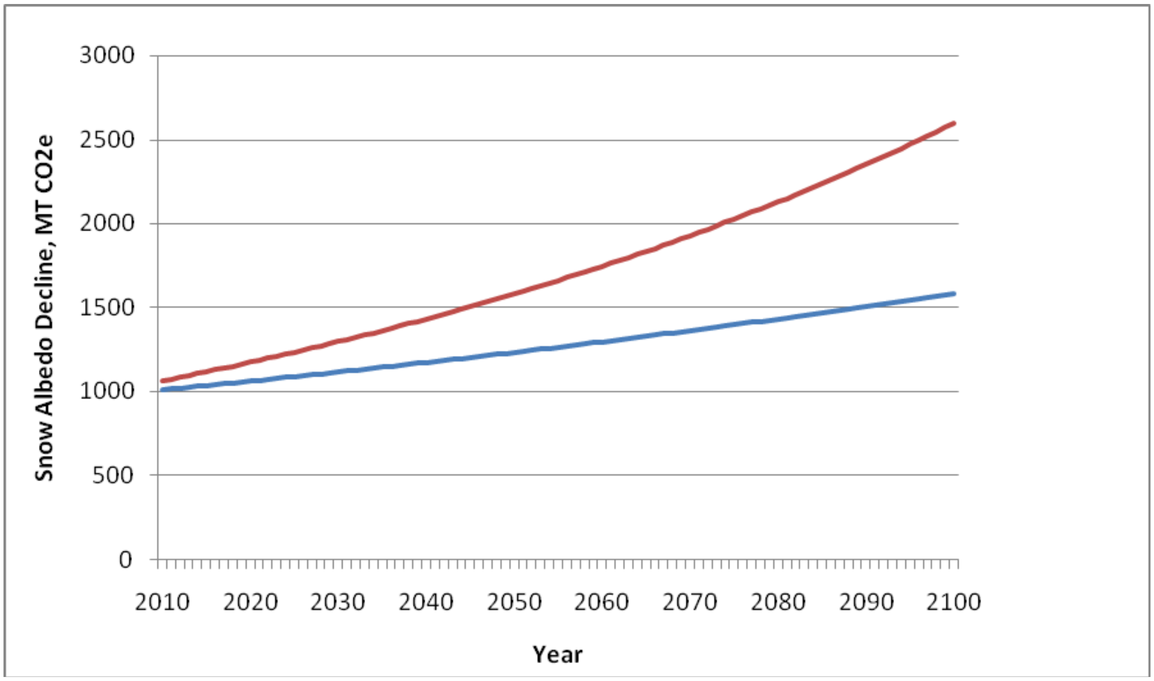

Figure 2. Range of Potential Annual Forcing Due to from Snow-Cover Albedo Declines (2010 to 2100), in MT (million metric tons) of CO_2e.

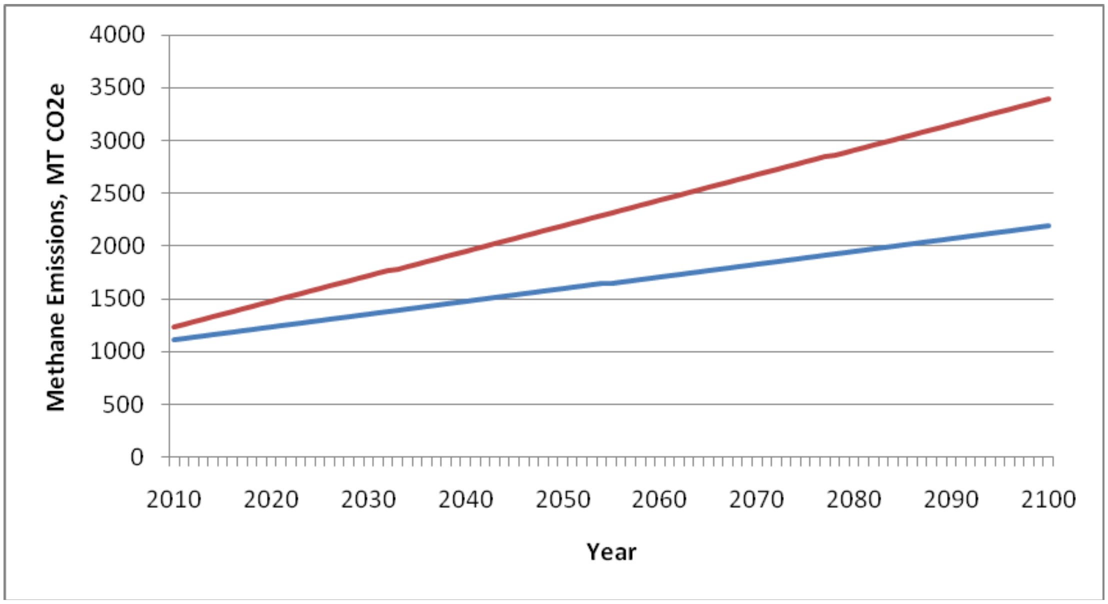

Figure 3. Range of Potential Annual Forcing Due to Increased Methane Emissions from Thawing Permafrost (2010 to 2100), in MT (million metric tons) of CO_2e.

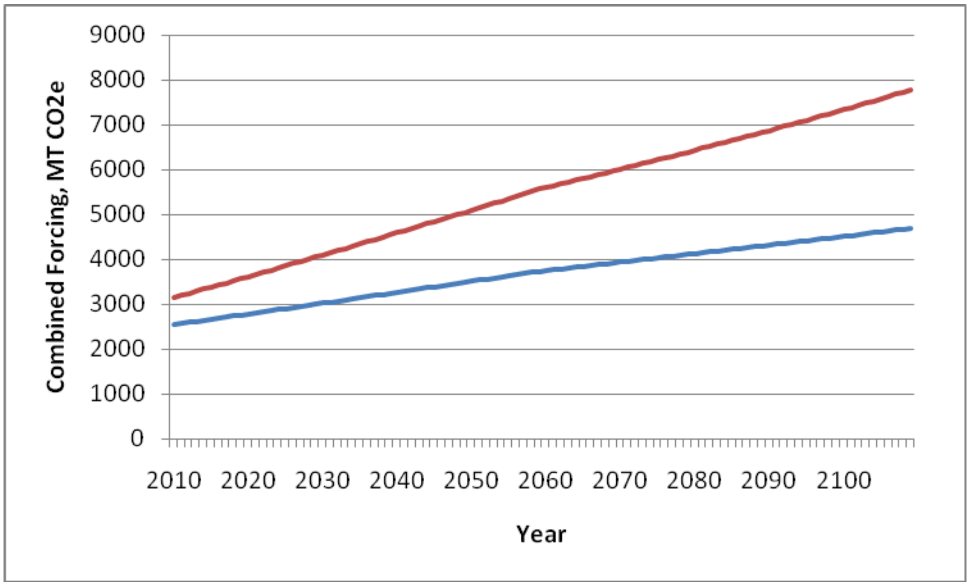

Figure 4. Range of Potential Annual Forcing Due to Combined Impacts (2010 to 2100), in MT (million metric tons) of CO_2e

As the figures show, total CO_2e impacts on the climate in 2010 are around 3,000 MT; this is equivalent to about 42 percent of current total US emissions of greenhouse gases. By mid-century, these potential impacts increase to a range of 3700 to 5600 MT and, by

2100,the range is 4700 to 7800 MT. At the upper end, these end-of-century Arctic emission equivalents would be greater than current US greenhouse gas emissions. The next section turns to an assessment of the costs that could be incurred by declining sea-ice and snow-cover albedo and increasing methane emissions due to thawing permafrost as they increase the heating of the planet.

4. Costs of Climate Change

Over the last twenty years, economists have developed procedures for estimating the “social costs of carbon”. A ton of carbon dioxide emitted this year will contribute to the heating of the planet for at least the next hundred years. In order to arrive at a single figure summarizing the costs incurred by that ton of carbon dioxide, it is first necessary to estimate the stream of annual additional costs that will be caused by the carbon dioxide, and then take the discounted present value of that stream.

There are at least four major assumptions made in estimating costs that generate uncertainties in the final estimate of the social cost of carbon in a given year:

1. Emissions trajectory: the quantity of global emissions and the resulting concentration of greenhouse gases in the atmosphere.
2. Climate sensitivity: the increase in temperature that will result from a given increased concentration of greenhouse gases.
3. Temperature-damage function: the economic impacts that will result from a given temperature increase.
4. Discount rate.

Economists frequently make assumptions regarding these four dimensions of the problem, and organize their analyses in the form of an integrated assessment model (IAM).[2] The model then generates estimates of the social cost of carbon in metric tons of CO_2 for a given year. We now turn to a discussion of the assumptions that drive differences in the results.

Emissions Trajectory. The first dimension that generates uncertainty in estimating the social cost of carbon is the trajectory of greenhouse gas emissions over the time period of the analysis, and the resultant concentration of heat-trapping greenhouse gases in the atmosphere. Most analysts assume that, through the relevant range, impacts rise at an increasing rate with temperature. This means that a ton of CO_2 released today will do more harm in its waning years (2100) if atmospheric concentrations of CO_2 at that time are at 780 ppm instead of 450 ppm. These two figures represent, respectively, the end-of-century outcome of the approximate current trajectory of global emissions, and the implicit current goal of the international community to hold warming to around 2°C

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[2] For a general critique of IAMs, see Ackerman et al. (2009b).

above 1990 levels. This assumption of rising marginal impacts also means that a ton of CO_2 released in the future will do more economic harm than a ton released today.[3]

Emissions trajectories depend in turn on assumptions about future population and gross domestic product (GDP) growth, as well as what policies are implemented at national and global levels to reduce the intensity of emissions per unit of GDP. The model results for the social cost of carbon reported below rely on a variety of scenarios for population growth and GDP growth put forward by the Intergovernmental Panel on Climate Change (IPCC), and reflect as well differing assumptions about imposed controls on emissions.

Climate Sensitivity. Once an emissions trajectory has been assumed, the second question is: How sensitive is the planet's temperature to increasing carbon dioxide levels in the atmosphere? The scientific literature through 2006 (IPCC, 2007) suggests that the most likely estimate for climate sensitivity is that a doubling of carbon dioxide concentrations above pre-industrial levels would lead to a 3°C warming. However, the IPCC stresses the uncertainty of this central estimate, and suggests that there is a 1 in 6 chance that the climate sensitivity is significantly higher, above 4.5°C.

The reason for this uncertainty, weighted towards the high end, is not only the possibility of positive feedbacks in the climate system—albedo changes and methane releases from tundra and thawing permafrost, or releases of methane from the gas hydrates of continental shelves—but also the possibility of regional-scale fire-driven deforestation, changes in low-level cloud cover, and other system-wide effects that could drive an upward spiral of temperature increases (Roe and Baker, 2007).

Recently, Hansen and his co-authors present significant evidence from the paleoclimatic record supporting a climate sensitivity of 6°C (Hansen et al., 2008). That is, they argue that the global warming that will result from any given increase in atmospheric concentration of CO_2 is twice as great as the IPCC projected in its Fourth Assessment. The estimates of the social cost of carbon reported below generally use underlying climate sensitivities ranging from 3°C to 6°C.

Temperature-Damage Function. Having assumed both future greenhouse gas concentrations and climate sensitivity, the third question becomes: What will the economic impact be of a given temperature increase? Calculating the social cost of carbon requires projections of the costs incurred by rising temperatures to the global economy, projections made over the next 100 years for temperatures outside the range of human experience. Impact estimates for a given amount of warming vary significantly.

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[3] We are ignoring discounting. See the discussion below on the assumed 3 percent growth rate for the social cost of carbon. The 780 ppm figure is an estimated trajectory following the 2009 Copenhagen commitments (see www.climateinteractive.org). Stern (2007) argues that at 450 ppm CO_2 (550 CO_2e) there is a 69 percent probability of exceeding a 2.4°C warming target, implying an even higher percentage probability of exceeding 2°C.

Richard Tol (2008), the original developer of the FUND integrated assessment model, points out that:

> "...cost estimates omit some impacts of climate change; they tend to ignore interactions between different impacts, and neglect higher order effects on the economy and population; they rely on extrapolation from a few detailed case studies; they often impose a changing climate on a static society; they use simplistic models of adaptation to climate change; they often ignore uncertainties; and they use controversial valuation methods and benefit transfers."

To illustrate this complexity, we compare the baseline cost estimates for the United States for one of the major integrated assessment models, DICE, developed by economist William Nordhaus (2008) at Yale, with an alternate set of estimates recommended by University of California—Berkeley economist Michael Hanemann (Table 1). Hanemann (2010) provides a category-by-category critique of Nordhaus, and recommends increasing the DICE baseline estimates by a factor of 4. The figures reported here are for a 2.5°C warming above 1990 levels.

	Nordhaus (DICE)	Hanemann
Market Impacts		
Agriculture	$6	$23
Energy	$0	$8
Water	$0	$15
Sea Level	$9	$53
Non-Market Impacts		
Health, Water Quality, Human Life	$3	$15
Human Amenity, Recreation, Leisure	-$26	$-8
Human Settlements and Ecosystems	$9	$17
Extreme and Catastrophic Events	$38	$38
Total	$39	$161
Excluding Extreme and Catastrophic	$1	$123

Table 1. Annual US Economic Impacts of a 2.5°C Warming, in $2008 Billions. Sources: Nordhaus, 2008 and Hanemann, 2010.

Table 1 begs many questions, and is used here primarily to illustrate that Nordhaus's DICE model is conservative in many of its underlying assumptions about climate change impacts when compared with the Hanemann model. Excluding the category of "Extreme and Catastrophic Events" (measured as annual national willingness to pay for insurance against the possibility of catastrophic events such as rapid sea level rise), Nordhaus's net overall annual US cost estimate is $1 billion—not even a rounding error in today's $14 trillion US economy.

Part of the reason for this low estimated cost is that Nordhaus assumes large recreational and amenity benefits ($26 billion) from warmer weather; for example, more good golf days.[4] Beyond that, his cost estimates by category are all in the low billions of dollars. Given that western US water supplies are expected to be dramatically impacted by declining snowpack (Goodstein and Matson, 2007), Nordhaus's assertion of a zero dollar figure for that category is surprising. Given likewise that a 2.5°C warming is anticipated to drive 20–30 percent of the species on the planet into extinction, including via accelerated acidification of oceans, the figure of $9 billion for ecosystems and human settlements combined also seems low (IPCC, 2007). The disparity between Nordhaus's and Hanemann's estimates provides a sense of the challenge economists face in estimating the impacts of future climate change.[5]

Uncertainty in the temperature-damage function is natural, because we do not fully understand the physical changes to the planet that will result from a given temperature increase. Consider for example the two estimates in Table 1 for sea-level rise costs: $6 versus $25 billion. As noted above, one of the primary ecosystem benefits of the frozen Arctic is the storage of vast quantities of water in the Greenland Ice Sheet. Plausible estimates of sea-level rise during this century—due to thermal expansion, melting of temperate glaciers, and the potential collapse of the Greenland and West Antarctic Ice Sheets—range from a manageable tens of centimeters to a truly devastating two meters (Pfeffer et al., 2008).

Despite the possibility of a sea-level rise of up to 2 meters, most economic analyses focus on 1 meter or less of total sea-level rise. Authors from the Massachusetts Institute of Technology (Sugiyama et al., 2008), for example, examine the case of a linear sea-level rise of 1 meter over the next hundred years, and assume that people in cities around the world rationally adapt by constructing sea-wall defenses wherever the benefits of construction are greater than the costs. This scenario results in a present value loss of wetlands, habitable land, and capital of approximately $2 trillion, discounted at 3–4 percent. Of course, the failure of New Orleans to prepare for the well-known dangers posed by a Katrina-like hurricane challenges the assumption of rational adaptation.

Beyond the loss of real-estate to rising waters, increased sea-level will expose more cities, more capital assets, and more people to New Orleans-style events, previously expected to occur only once in every 100 years. With no permanent inundation, that single storm still caused more than $100 billion in property and other types of damage, and forced the evacuation of more than 1 million people. A recent study by the Organisation for Economic Co-operation and Development (OECD) suggests that only a half a meter of sea-level rise—towards the lower end of projections—will, by 2070, put more than 70 million people and $8 trillion in additional assets at risk of exposure to 100-year storm surges (Nicholls et al., 2008a). With more than 100 major cities exposed, we

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[4] Recreational and amenity benefits are large in Nordhaus and Boyer because they include the subjective enjoyment of a warmer climate (see discussion below).

[5] Ackerman et al. (2009a) show that results generated by DICE are quite sensitive to the choice of a key parameter in the damage function.

should expect that incremental exposure to translate into substantial human and capital losses on average once a year.

The point here is that 1 meter or less of sea-level rise will be costly. Although there are few concrete estimates, sea-level rise of more than that will undoubtedly be very costly.[6] Impacts are likely to rise at an increasing rate since each additional centimeter of sea level rise exposes more people and infrastructure to risk and damage. At the same time, we have as yet no way of knowing whether the high-end or mid-range estimates of sea-level rise are more likely. What holds true for sea-level rise also holds for agriculture, water supply, public health, ocean acidification, forests, recreation and leisure. In the face of this uncertainty, this paper will use model estimates of the social cost of carbon reflecting a range of different assumptions about the temperature-damage function.

Discount Rate. Controversies over discounting are well known. Briefly, economists generally measure future benefits and costs in present value terms, as the amount of money that would have to be invested today at the going rate of return to generate a comparable cost or benefit in the future. Discounting is integral to decision-making in a cost-benefit framework, but is problematic over long-time horizons.

In the case of global warming, the argument for discounting is as follows. Preventing impacts from CO_2 emissions—for example by building a sea-wall or investing in solar energy—bears an opportunity cost. The incremental dollars spent on sea walls or solar panels might have built a school or financed research and development in new pharmaceuticals. Discounting future climate costs insures that society does not over-invest today in stabilizing the climate, but instead weighs those investments equally with other investments of potential benefit to future generations.

The argument for discounting is most persuasive when analyzing the benefits and costs of projects with a time-horizon occurring within a single investor's lifetime, such as a 30-year mortgage. However, a ton of CO_2 released today will continue to impose economic costs for at least 100 years. Table 2 illustrates how discounting truly does "discount" costs that are incurred in the future. Costs of $100 that occur at the end of this century are reduced to a present value of $40.90 at a discount rate of 1 percent, $7.00 at 3 percent, and only $1.20 at 5 percent.

Discount Rate	Cost in 2100	Present Value of Cost in 2010
0.01	$100	$40.90
0.02	$100	$16.80
0.03	$100	$7.00
0.05	$100	$1.20

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[6] Nicholls et al. (2008b) explore the case of a 5-meter, 100-year sea-level rise resulting from a hypothetical, rapid collapse of the Greenland and/or West Antarctic Ice Sheets. Some 400 million people *currently* live in land that would be potentially inundated. Actual inundation and relocation would depend on the degree of coastal protection initiated, which in turn would be quite costly.

Table 2. The Impact on $100 of Cost in 2100 of Discount Rates from 1–5 Percent.

For short-time horizon cost assessments, discount rates of 3 to 5 percent are reasonable; they often reflect the foregone opportunity costs of investing dollars in one area and not another. When discounting at 5 percent, however, a logic that tells us not to spend $1.20 today to prevent, in 90 years, $100 in economic costs to our descendants is troubling to most people, including many economists. Discount rates that rise above 3 percent result in analyses that dramatically reduce the present value of any costs to people or the planet beyond a 30 to 40 year time horizon, largely excluding climate impacts on future generations from the cost-benefit calculus.

Lack of intergenerational equity may be the best-known and most intuitive criticism of the use of high discount rates for long-time horizon analyses. This concern has been reinforced by numerous economic studies focusing on a number of other technical issues described here. (1) Climate investments are, in significant part, a kind of insurance motivated by risk aversion to avoid catastrophic outcomes. Investment in insurance (e.g., purchase of a fire insurance policy) typically has a negative rate of return. It is undertaken to minimize worst-case losses, not to maximize average gains (Weitzman, 2009; Ackerman et al., 2009a). (2) It is likely that in general climate stabilization investments will have a higher pay-off in the future during periods when economic growth rates are small. Under these conditions, economic theory requires a correspondingly small discount rate (Howarth, 2003). (3) Regardless of risk correlation, empirical evidence suggests that revealed discount rate choices are heavily influenced by the variance of the potential financial gain facing investors. For investments with little investment risk of this type (e.g., many climate stabilization investments), the appropriate discount rate is also low (Howarth, 2009). (4) Since future economic growth rates are inevitably uncertain, the appropriate discount rate for long-term analyses is one that is gradually declining over time. If all else remains constant, significant risks of future low economic growth or catastrophic outcomes will cause the rate to decline faster (Weitzman, 1998). (5) Growth in material consumption in developed countries does not correlate highly with increases in subjective well-being. As a result, the opportunity cost of climate investments should be calibrated against increases in per capita net national welfare, not to increases in per capita consumption, as the latter grows more slowly than the former (Goodstein, 2007). All of these issues cast considerable doubt on the validity of using discount rates greater than 3 percent for evaluating long-run benefits and costs of climate change mitigation.[7]

Given these issues, the US EPA (2008) concludes:

> "OMB's [Office of Management and Budget's] Circular A-4 general analytical guidance requests use of constant 3% and 7% discount rates for both intra- and inter-generational discounting and allows for low but positive consumption discount rates if there are important intergenerational benefits or costs (e.g., 1–3%

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[7] For a good review of discounting in the context of climate change, see Stern (2007).

> noted by OMB, 0.5–3% by EPA).… A review of the literature indicates that rates of three percent or lower are more consistent with conditions associated with long-run uncertainty in economic growth and interest rates, inter-generational considerations, and the risk of high impact climate damages (which could reduce or reverse economic growth)."

In spite of the many persuasive arguments against the use of high discount rates, and in direct contradiction to the 2008 US EPA guidance just quoted, a recent regulatory proposal by the US EPA and the National Highway Traffic Safety Administration (NHTSA) relies on a social cost of carbon that was estimated from integrated assessment model runs employing 3 percent and 5 percent discount rates (US EPA/NHTSA, 2009). The decision to rely exclusively on rates of 3 percent or greater is not well supported.[8] In fact, of the 12 model runs employed by the agency using the 5 percent discount rate, more than half conclude that there will be *either zero economic costs or positive net benefits* to human society from business-as-usual global warming, i.e., around 3°C over current temperatures by 2100.

This rather surprising result emerges because one of the integrated assessment models used, FUND, assumes large positive impacts from mild global warming in the early years, that are later overwhelmed by economic costs as the earth's atmosphere continues to warm up. However, at the 5 percent discount rate, the later impacts and costs are more than offset by the early benefits, leading the model to conclude that humans are better off, on net, with business-as-usual global warming. DICE has a similar structure with large initial benefits. In its latest iteration, however, the model finds that at a 5 percent discount rate business-as-usual global warming has positive, but very small, net costs. What are these up-front benefits?

As noted above, DICE assumes large amenity and leisure benefits from the early stages of warming—for example, people will have longer fall and spring seasons for outdoor recreation. FUND includes an assumption that on net, a reduction in cold-related deaths will greatly outweigh an increase in heat-related deaths. FUND's designer, Richard Tol (2008), and co-authors have argued that a 1°C increase in the global mean temperature would save, on net, more than 800,000 lives a year by 2050. Both models also assume

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[8] US EPA/NHTSA provides two paragraphs of justification for the 5 percent rate. The first argues that climate investments should be considered risky investments—comparable to corporate stocks—as their payoffs are uncertain. In fact, as US EPA/NHSTA acknowledges, the appropriate choice of discount rate is not determined by risk per se, but by the correlation of risk with the performance of the broader economy. And as noted above, as insurance investments, climate investments will likely have their highest payoffs when economic outcomes are not positive. The second paragraph cites five sources in support of 5 percent as a "standard estimate" from the literature for Ramsey discount rates. In fact, there is no standard estimate, and of the five sources cited, only one recommends the use of a 5 percent rate for assessing long-run damages, and it does so in a qualified way. These points are made in Ackerman (2009).

that agriculture will initially benefit from CO_2 fertilization and longer growing seasons, before eventually experiencing net costs.

DICE assumes that human enjoyment of the weather is maximized at a year-round average temperature of 20°C. As Ackerman et al. (2009b) note: "...this is roughly the temperature of Houston or New Orleans, cities where anyone who can afford it uses air conditioning for most of the year; it is well above the current global average temperature of about 14.5°C." Redhanz and Madison (2005) find that outside of the most northern countries, there will be few amenity benefits from even the first few decades of warming.

Regarding the health benefit estimates in FUND, Ackerman and Stanton (2008) demonstrate that their existence depends on the questionable assumption that humans would not adapt to local temperature changes. Finally, the magnitude of alleged agricultural benefits has been challenged by Schenkler et al. (2005), Hanneman (2010), and others. This debate over whether or not large benefits from global warming exist in the short-term brings us back to the difficulty of specifying temperature-damage functions and provides yet another example of the perverse impacts of high discount rates.

Even assuming that the amenity, health and short-term agricultural benefits identified by Nordhaus and Tol are real, the 5 percent discount rate clearly privileges these short-term net benefits enjoyed by the current generation, as the planet warms slightly, over longer term net costs imposed on our grandchildren and generations to follow, as the earth heats up dramatically. The result is a model outcome arguing the counterintuitive case that unchecked global warming will, on balance, benefit humanity. For this reason—as well as for all of those discussed above—we are reluctant to utilize the US EPA/NHTSA estimate of social costs that is based on an averaging of models using 3–5 percent discount rates. Nevertheless, as the number has recently been employed by a G-7 country in a proposed rule-making, for the purposes of this paper, we will utilize the social cost of carbon generated using these high discount rates. We will also use estimates from models employing discount rates ranging from 1.4 percent to 3 percent.[9]

With this understanding of the reasons for variation in the estimated social cost of carbon, we now turn to representative model outputs.

Social Cost of Carbon Estimates. Table 3 illustrates the range of estimates for the social cost of carbon generated by various integrated assessment models, depending on the underlying assumptions.

	Very Low	EPA/NHTSA	EPA 3	Stern	Very High
Social Cost of Carbon, 2010 ($2008 per metric ton CO_2)	$13	$22	$46	$104	$798

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[9] Stern (2007) employs the 1.4 percent rate; US EPA (2008) relies on rates of 3 percent and 2 percent for their analyses.

Source	Tol (2008)	US EPA/NHSTA (2009)	US EPA (2008)	Stern (2007)	US EPA (2008)
IAM Discount Rate	≥5%	3%-5%	~3%	1.4-2.7%*	~2%

*Stern-like results can be generated using discount rates as high as 2.7 percent. See footnote 13.

Table 3. Estimates of the 2010 Social Cost of Carbon, in \$2008 per metric ton CO_2

The very low, "best case" estimates assume optimistic emissions scenarios, low climate sensitivity, low estimated impacts arising from given temperature increases, and high (≥5 percent) discount rates. Combined, these assumptions generate social cost of carbon estimates of approximately \$13 per metric ton.[10]

At the other extreme, high emission levels, high climate sensitivity, high impacts and costs from a given temperature increase, all combined with low discount rates, generate the very high estimates—\$798 per ton in the representative case listed, which is a US EPA run of the FUND integrated assessment model. Other models also generate comparably large carbon costs. For example, Ackerman et al. (2009a) ran DICE utilizing a 2.7 percent consumption discount rate, a climate sensitivity of 6, and also altered the model's temperature-damage function to reflect what the authors viewed as more likely costs from a given temperature increase than are found in standard DICE. With these assumptions, and under the DICE "no-control" emission scenario, the estimated 2010 social cost of carbon is \$445.[11]

Cost of carbon estimates in this high range reflect movement in the direction of rapid climate change, with temperature increases of 6°C by the end of the century. This kind of scenario would, in the words of Harvard economist Martin Weitzman (2007), leave our children inhabiting a "terra incognita biosphere"—an unrecognizable world. The impacts would likely encompass: a sea-level rise of two meters; transformation of the mid-western and southwestern United States into conditions of permanent drought; loss of summer water supply for over a billion people in the western Americas and Asia; and rapid mass extinction of a large percentage of life on earth. Unfortunately, this tail of the outcome distribution is uncomfortably fat; Weitzman argues that we do not have enough information to rule out this dangerous possibility with any confidence. His reading of IPCC estimates implies that the probability of this kind of worst-case outcome is on the order of 3 percent, and higher as we move beyond 2100.

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[10] This is Tol's (2008) summary of models with "conservative assumptions"—consumption discount rates of 5 percent or greater—adjusted here to 2008 dollars, and to reflect 2010 emission impacts via a 3 percent per year growth rate from 1995.

[11] Specifically, Ackerman et al. (2009a) increase the DICE damage function exponent from 2 to 3. The US EPA (2008) figure of \$798 in Table 3 is derived from the Global FUND run with a 2 percent discount rate, a climate sensitivity of 6, and a high-end IPCC emissions scenario, adjusted here to \$2008 and to reflect 2010 emission impacts via a 3 percent per year growth rate from 2006 (see discussion below).

Between these very low and very high extremes for the social cost of carbon, there are three estimates in Table 3 labeled *EPA/NHTSA*, *EPA 3*, and *Stern*.

EPA/NHTSA. As part of a proposed rule-making for light-duty vehicle emissions, US EPA/NHTSA (2009) recommended a social cost of carbon of $20 per ton. The agencies rely on a weighted average of published results from only three integrated assessment models, FUND, DICE and PAGE. As noted in the discussion of discount rates above, the estimate is a weighted average of model runs relying on 3–5 percent discount rates. Also as noted above, our judgment is that recent economics literature does not support the use of such high discount rates for the analysis of climate change impacts; nevertheless, we include the figure as it has been used in a recent proposed rule-making in the United States. The 2010 EPA/NHTSA estimate in Table 3 of $22 adjusts the original 2007 figure to $2008 and to reflect 2010 emission impacts (see discussion below).

EPA 3. US EPA (2008) derives a social cost of carbon estimate for the baseline year 2007 through a meta-analysis of the literature, following Tol (2008), but focusing on studies authored after 1995. Through this process, the US EPA derived a series of estimates for the year 2007 social cost of carbon. The $46 per metric ton figure is the mean from the US EPA study, restricted by US EPA to analyses employing a 3 percent consumption discount rate, adjusted to $2008 and to reflect 2010 emission impacts (see discussion below).

Stern. In 2006, former World Bank Director Sir Nicholas Stern issued a well-known UK government report (published in book form in 2007) that estimated the social cost of carbon at $87 per metric ton. Stern relied on a lower consumption discount rate (1.4 percent) than most previous authors, and used more inclusive temperature-damage relationships than are found, for example, in DICE. Subsequent formal modeling analyses using major integrated assessment models such as PAGE, DICE and FUND reinforce the point made in our discussion above: the integrated assessment model results are assumption driven, with Stern-like assumptions generating Stern-like costs of carbon.[12] The 2010 Stern estimate in Table 3 of $104 adjusts the 2006 figure to $2008 and to reflect 2010 emission impacts (see discussion below).

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[12] The central estimate for US EPA's (2008) meta-analysis using 2 percent consumption discount rates (as opposed to the 3 percent estimate in Table 3) is $78 per ton. Ackerman et al. (2009a) ran DICE using a consumption discount rate of 2.7 percent, a climate sensitivity of 6, a damage exponent of 3, and an optimal emissions response to get an estimate of $96 per ton. Hope (2006) ran the PAGE model using Stern's discount rate and a somewhat higher distribution of climate sensitivities, generating an estimate of $115 per ton. Anthoff et al. (2009) are highly critical of Stern, and yet modeling one of Stern's concerns—equity impacts in the developing world—using FUND, arrive at an estimate of $58 per ton. (All estimates in this paragraph are in $2008 and are adjusted to reflect 2010 emission impacts).

In addition to helping guide UK climate policy, the Stern report has gained acceptance by a broad group of influential economists and policy-makers, though it has critics as well. Among the list of prominent economists supporting Stern-like conclusions (some of whom argued he was right, but for the wrong reasons) include five Nobel Laureates—Arrow (2008), Stiglitz (2006), and Mirlees, Solow and Sen (quoted in Stern, 2007)—as well as Weitzman (2007), Sterner (2008) Sachs (quoted in Stern, 2007), Barker (2008), and Ackerman et al. (2009a). Tol (2008; writing with Anthoff et al. (2009) and in many other venues) has been the most vocal Stern critic. The United Kingdom currently uses a "non-traded price of carbon" for cost-benefit analysis of $80 per ton (UK DECC, 2009). This is explicitly not a social cost of carbon estimate, but is, rather, a carbon price chosen to achieve the UK emission reduction targets.

To summarize: economists have derived social cost of carbon estimates using integrated assessment models. These models have many limitations, and as a result of omissions and simplifications are widely believed to underestimate the social cost of carbon.[13] The major driver of differences in the model results is the choice of discount rate. The US EPA (2008), following much recent literature, recommends that for evaluating the social cost of carbon, discount rates of 3 percent or less be employed. Given this, EPA 3 ($46 per metric ton) and Stern ($104 per metric ton) represent important poles for policy, with the recognition that the real cost of carbon could be somewhat lower, or much higher than this range. US EPA/NHTSA (2009) illustrates how a higher choice of discount rates dramatically reduces the assessment of the cost of future climate impacts. Looking only at results from three models, and using 3–5 percent discount rates, this source develops an estimate of $20 per metric ton. We use these different estimates for the social cost of carbon as 2010 starting points to bracket our assessment of the cost of a warming Arctic.

As noted above, because a ton of carbon emitted into a future, hotter world would have a greater impact than a ton emitted today, the cost of carbon will rise over time. Following the IPCC (2007), the US EPA (2008) increases the per metric ton social cost of carbon estimates by 3 percent per year. We follow that procedure here.

5. The Cost of a Warming Arctic

Table 4 illustrates the estimated economic costs resulting from a thawing Arctic using: three different estimates of the social cost of carbon; and the high, medium and low range estimates of increased forcing due to changes in sea-ice and snow-cover albedo and increased methane releases. The net present value (NPV) of cumulative costs from global warming impacts are presented using the approximate discount rate used for calculating the social cost of carbon for each estimate within the integrated assessment models employed. These are, respectively, 4 percent, 3 percent and 2 percent, again with the caveat that we view 4 percent as an inappropriately high discount rate for evaluating intergenerational costs and benefits.

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[13] As noted by the IPCC (2007), "It is very likely that globally aggregated figures underestimate the damage costs because they cannot include many non-quantifiable impacts."

The column labeled *EPA/NHTSA* uses the \$22 estimate for the social cost of carbon, the low end CO_2 equivalent forcings from Figure 4, and evaluates cumulative impacts at 4 percent. For the year 2010 alone, the estimated global costs that will occur as a result of this increased planetary warming is \$61 billion. This rises to a cumulative total by 2050 of \$2.4 trillion. Over the century, the cumulative effects are estimated to be \$4.9 trillion.

YEAR	EPA/NHTSA	EPA 3	Stern
2010	$61	$146	$371
2010–2050	$2,401	$7,349	$24,111
2010–2100	$4,857	$19,842	$91,275
Social Cost of Carbon	$22/T CO_2e	$46/T CO_2e	$104/T CO_2e
IAM Discount Rate	3%-5%	3%	1.4%-2.7%*
NPV Discount Rate	4%	3%	2%
CO_2e Scenario, Fig.4	Low	Mid-range	High

*As noted in Table 3, Stern-like estimates can be generated using discount rates as high as 2.7 percent. See footnote 13.

Table 4. Estimated Costs of Lost Climate Services from a Warming Arctic, in Billions of $2008

The second column, labeled *EPA 3*, uses the $46 estimate for the social cost of carbon, mid-range CO_2 equivalent forcings from Figure 4, and a 3 percent discount rate.[14] Here, the year 2010 emissions equivalents alone are projected to do economic harm valued at $146 billion. The 2010–2050 cumulative impacts are projected to rise to $7.3 trillion. Over the entire period, 2010–2100, the cumulative estimated economic costs rise to $19.8 trillion.

Finally, the last column uses the Stern estimate for the social cost of carbon, the high-end CO_2 equivalent forcings from Figure 4, and discounts cumulative impacts at 2 percent. For the year 2010, the estimated global costs are $371 billion. This rises to a cumulative total by 2050 of $24.1 trillion. Over the century, the cumulative economic costs are estimated to be $91.3 trillion.

Even at the low end, these are large numbers, reflecting emissions equivalents from Arctic albedo declines and increased methane releases that are currently about 42 percent of US total greenhouse gas emissions, and that are projected to at least double in magnitude over the coming century. Consider the mid-range estimate of 2010–2050 cumulative impacts: $7.3 trillion. This is equivalent to the annual GDP of Germany, Russia, and the United Kingdom combined. Policies that maintain and, in the long run, restore a frozen Arctic would enrich the world at a significant rate.

There is wide variance in the estimates in Table 4. The initial 2010 estimates vary by a factor of 5; the cumulative impacts vary by a factor of 20. Again, it should be pointed out that in both cases, much of the variance is being driven by the choice of discount rate, with the other assumptions discussed above playing smaller roles. Variance in the 2010 cost estimates results from discount rates embedded in the integrated assessment model estimates of the social cost of carbon. The even wider variance in the cumulative impacts

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[14] The mid-range figure is not shown in Figure 4; it is calculated as the average of the high and low.

is compounded by a second round of discounting, at varying rates, to obtain the net present value of the emissions costs.

6. Conclusion

The frozen Arctic provides immense services to all nations by cooling the earth's temperature—the cryosphere acts like an air conditioner for the planet. As the Arctic melts, this critical, climate-stabilizing ecosystem service is being lost, and this paper provides a first attempt to monetize the cost of some of those lost services.

We do not address here worst-case scenarios, such as a warming planet that triggers massive releases of methane-hydrates from Arctic soils and ocean-beds (Anthony, 2009). Rather, the purpose of this paper is to illustrate that observed changes in the Arctic sea-ice and snow-cover albedo, and Arctic methane releases from thawing permafrost, are already generating large economic costs at an estimated rate of $61–371 billion annually. With future declines in albedo and increases in methane releases both being likely, the cumulative cost impact over the next 90 years could reach trillions or tens of trillions of dollars.

Some popular discussion has suggested that as the Arctic melts, new-found treasures below the sea-bed will be unlocked. This paper emphasizes instead that an Arctic that remains frozen delivers significant global value. Over the next few decades, further warming of the Arctic is highly likely. Yet, over the longer term, humans could return the planet to a state in which the Arctic cryosphere begins to recover and once again contributes its full economic value as a climate-stabilizing force. Recently, IPCC Chair Rajendra Pachauri stated the desirability of a 350 ppm long-term goal for CO_2 concentrations in the atmosphere (Johnson, 2009). One important benefit of that policy goal would be the restoration of a significant portion of the climate stabilization services of the frozen Arctic identified here.

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