Ecological Applications, 23(8), 2013, pp. 1869–1880

An estimated cost of lost climate regulation services caused by thawing of the Arctic cryosphere

Eugénie S. Euskirchen,[1,4] Eban S. Goodstein,[2] and Henry P. Huntington[3]

[1]*Institute of Arctic Biology, University of Alaska Fairbanks, Fairbanks, Alaska 99775 USA*
[2]*Bard Center for Environmental Policy, Bard College, Annandale-on-Hudson, New York 12504 USA*
[3]*Pew Charitable Trusts, Eagle River, Alaska 99577 USA*

Abstract. Recent and expected changes in Arctic sea ice cover, snow cover, and methane emissions from permafrost thaw are likely to result in large positive feedbacks to climate warming. There is little recognition of the significant loss in economic value that the disappearance of Arctic sea ice, snow, and permafrost will impose on humans. Here, we examine how sea ice and snow cover, as well as methane emissions due to changes in permafrost, may potentially change in the future, to year 2100, and how these changes may feed back to influence the climate. Between 2010 and 2100, the annual costs from the extra warming due to a decline in albedo related to losses of sea ice and snow, plus each year's methane emissions, cumulate to a present value cost to society ranging from US$7.5 trillion to US$91.3 trillion. The estimated range reflects uncertainty associated with (1) the extent of warming-driven positive climate feedbacks from the thawing cryosphere and (2) the expected economic damages per metric ton of CO_2 equivalents that will be imposed by added warming, which depend, especially, on the choice of discount rate. The economic uncertainty is much larger than the uncertainty in possible future feedback effects. Nonetheless, the frozen Arctic provides immense services to all nations by cooling the earth's temperature: the cryosphere is an air conditioner for the planet. As the Arctic thaws, this critical, climate-stabilizing ecosystem service is being lost. This paper provides a first attempt to monetize the cost of some of those lost services.

Key words: *economic cost; ecosystem services; methane; permafrost; sea ice; snow cover.*

Introduction

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. The warming is expected to continue through the 21st century (ACIA 2005). The greater rate of warming in the Arctic is due in large part to 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 feedbacks are stronger than the negative feedbacks (McGuire et al. 2006).

One of the better known feedbacks is the snow and ice albedo (i.e., reflectivity) feedback loop. In the Arctic, this loop is strong since the snow and ice surface is generally bright. As snow or ice melts, a darker surface is exposed, less solar energy is reflected back to space, and more energy is absorbed, which then heats the atmosphere, resulting in yet more melt, greater absorption of solar energy, and further temperature rise. Another potentially strong positive feedback loop in the Arctic is related to methane releases from the thawing of permafrost. Rising air temperatures cause increases in emissions of methane from permafrost soils (Zhuang et al. 2004, 2006), which in turn raise atmospheric greenhouse gas concentrations, leading to a further increase in temperature, and more thawing of permafrost. Accurately quantifying these feedback loops and their interactions is a challenging endeavor, but as warming continues, it is likely that these feedbacks will intensify.

Changes in the cryosphere will have far-reaching ecological, climatic, and economic impacts that we are just beginning to understand. On a global scale, the reflective surface of ice and snow has a cooling effect. Sea ice formation and melt helps drive the world's ocean currents, permafrost traps vast quantities of carbon, which can be released as the potent greenhouse gas methane. However, there is little recognition of the significant loss in *economic value* that the disappearance

Manuscript received 11 May 2011; revised 3 February 2012; accepted 19 March 2012. Corresponding Editor: M. Sturm. For reprints of this Invited Feature, see footnote 1, p. 1743.
[4] E-mail: seeuskirchen@alaska.edu

TABLE 1. Estimates of the 2010 social cost of carbon (SCC), US$ (2008) per metric ton CO_2.

Parameter	Scenario used to compute the social cost of carbon			
	Very low	IAWG	Stern	Very high
2010 SCC (US$ [2008]/Mg CO_2)	$13	$22	$104	$798
Source	Tol (2008)	U.S. EPA and NHSTA (2009)	Stern (2006)	U.S. EPA (2008)
IAM discount rate	≥5%	3%	1.4–2.7%†	~2%

Notes: IAM stands for integrated assessment model.
† Stern-like estimates can be generated using discount rates as high as 2.7% (see Ackerman et al. 2009*b*).

of Arctic sea ice, snow, and permafrost will impose on humans.

This paper describes a first-order analysis of selected global ecosystem services provided by the Arctic cryosphere in the form of climate regulation. We quantify global economic effects arising from additional global temperature increases due to the albedo and permafrost changes described in the preceding paragraphs. We convert the additional planetary warming caused by these three changes in the Arctic cryosphere into annual CO_2 equivalents (CO_2e), and then calculate the global economic costs of extra warming induced by the changes. We do this utilizing two different social cost of carbon estimates taken from the literature, estimates that have been used by policy-makers in the United States and UK. The social cost of carbon attempts to measure the present discounted value of, typically, the 100-year stream economic damages resulting from the extra warming arising from 1 metric ton (1 Mg) of CO_2 emitted into the air. The global costs imposed by the breakdown of the natural cooling functions of the Arctic are then provided for 2010, and cumulatively through the years 2050 and 2100.

These three ecosystem functions of the cryosphere were chosen because the changes in these systems act as strong positive feedbacks to a warming climate. Furthermore, observations and modeling results are reasonably consistent and provide a relatively clear picture of what has happened and what is likely in store for the 21st century. Other components and global effects of the cryosphere are not addressed here due to greater complexity, with the result that our estimates of costs are partial, and also likely underestimate the full costs of loss of the frozen Arctic. In *Discussion*, we note that large negative feedbacks, that would substantively affect our results, seem unlikely to emerge as the Arctic warms.

METHODS

Overview

Relative to a preindustrial Arctic, and relying on estimates in the literature, we first calculate the approximate added global radiative forcings arising from projected changes in Arctic sea ice, snow cover, and methane emissions from degrading permafrost for each of the years 2010–2100. Radiative forcing is a measure of the balance between incoming solar radiation and outgoing infrared radiation of the Earth-atmosphere system, expressed in units of W/m^2. The balance is influenced when factors that affect climate are altered (e.g., changes in sea ice or snow cover). A positive forcing represents a heating effect, while a negative forcing represents a cooling effect.

Our second step is to convert these forcings to CO_2 equivalent (CO_2e) emissions. For each of the three cryosphere changes, 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 next surveyed the range of social cost of carbon estimates of warming damages per metric ton of CO_2e that have been developed by economists using integrated assessment models. We select two mid-range estimates, one used by the U.S. government, the other by the UK government, and utilize these damage estimates to assess the global cost of the breakdown of the Arctic's natural cooling services for each year, 2010–2100, in 2008 U.S. dollars (US$). We present results for 2010, as well as the present value of cumulative costs through 2050 and 2100. For the cumulative estimates, we discounted damage estimates for years beyond 2010 using a discount rate consistent with the economic model that generated the social cost of carbon employed (Table 1).

Calculation of the forcing from albedo changes and terrestrial methane releases

Sea-ice–albedo feedback.—The extent of Arctic summer sea ice has declined since the beginning of the record in 1953, with the lowest values recorded in 2007 and again in 2011, the second lowest in 2008, and the third lowest in 2009 (Fig. 1; Table 2; Stroeve et al. 2007). 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 summer sea ice extent decline continues, then the Arctic Ocean may become seasonally ice free by the middle of the 21st century, or possibly earlier (Holland et al. 2006; Table 2). 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

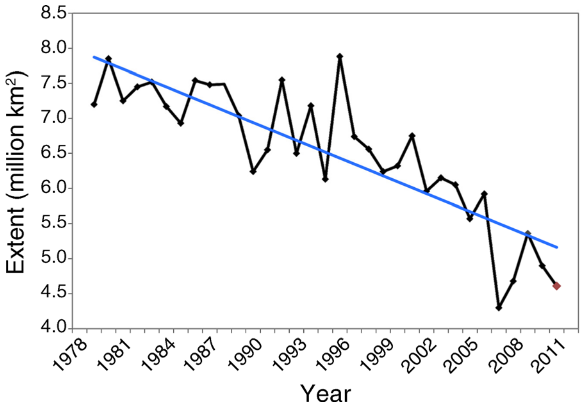

FIG. 1. Mean monthly Arctic sea ice extent, September 1979–2011 (the black line shows the actual data, and the blue line is the linear regression line fit to the data). The September rate of sea ice decline is 12% per decade relative to the 1979–2000 average. The figure is from the National Snow and Ice Data Center.

winter, and may then hasten the degradation of certain types of permafrost (Lawrence et al. 2008).

As noted above, the effect of the disappearance of summer sea ice is a projected amplification of climate warming due to the ice–albedo feedback loop. To determine the change in radiative forcing due to the loss of summer sea ice, we used the results of sensitivity tests in modeling studies (Rind et al. 1995, Bony et al. 2006) that showed that 20–40% of the increase in radiative forcing in response to forcing from projected increases in CO_2 ($\sim$700 ppm by 2100, with estimates ranging between $\sim$560 and 800 ppm; e.g., Euskirchen et al. 2009) is due to sea ice loss and the associated increase in solar absorption. This globally averaged increase in radiative forcing due to CO_2 increases is roughly 4 W/m^2 by 2100 (noting that literature estimates range from 3.7 to 4.4 W/m^2; e.g., Cess et al. 1993, Forster et al. 2007). Specifically, based on the model estimates for year 2100 (Rind et al. 1995, Bony et al. 2006), we calculate that sea ice loss is expected to exert 0.8–1.6 W m^{-2} (e.g., 20–40% of the 4 W/m^2) on the top of the atmosphere radiation budget due to the resulting darker surface that absorbs 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 700 ppm represents a an estimate of the CO_2 concentration in 2100 (e.g., Euskirchen et al. 2009) 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 $0.8(500/700) = 0.57$ 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. 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. Since the goal of this work is to understand the total economic costs, we focus less on the forcing for a given year, and by extension the cost for a given year, and more on the decadal and cumulative forcings and costs. To the extent that forcings and costs are in fact delayed, positive discounting implies that our present value cost estimates would be higher than the true values, with this cost then depending on the amount of time that the forcings are delayed.

In order to apply our estimates of warming to the economic cost analysis (described in *Computing the cost: integrated assessment models*), we needed to translate this warming in W/m^2 into CO_2 equivalents through the year 2100. We did this based on the methodology outlined in Zhuang et al. (2006) and Euskirchen et al. (2010). 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 again used the estimate that globally a 4.0 W/m^2 radiative forcing change is caused by a doubling of atmospheric CO_2 (once more, noting that literature estimates range from 3.7 to 4.4 W/m^2; e.g., Cess et al. 1993, Forster et al. 2007). At 350 ppm CO_2, there is roughly 700 Pg C storage, corresponding to 1400 Pg C storage at 700 ppm, taking into account the fertilization effect of increased atmospheric CO_2 on terrestrial and marine ecosystems (Prentice et al. 2001, Denman et al.

TABLE 2. Estimates and references for changes in summer sea ice, snow cover duration (days per decade shorter), and methane emissions (increase in Tg CH_4/yr).

Component	Estimate of change	Reference
Sea ice	11.2% area loss per decade between 1979 and 2009	NSIDC
Snow cover	2.5 days per decade across the pan-Arctic between 1970 and 2000	Euskirchen et al. (2007)
Terrestrial methane emissions	1.3 Tg CH_4/yr increase between 2003 and 2007 from Arctic wetlands	Bloom et al. (2010)
	0.6 Tg CH4/yr between 1997 and 2006 from Arctic wetlands	McGuire et al. (2010)
	0.5 Tg CH_4/yr increase between 2002 and 2100 from wetlands throughout northern high latitudes	Zhuang et al. (2006)

Note: NSDIC stands for the National Snow and Ice Data Center.

2007). 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; Lutgens et al. 2008) 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. To do this, we calculated the atomic weight of C (which is 12) and O_2 (which is 16). Consequently, the atomic weight of CO_2 is 44, and that of C is 12, giving a multiple of 44/12 or 3.67, to get 1259 CO_2e per m^2 (that is, 343×3.67).

Snow–albedo feedback.—Currently, the snow cover (e.g., days with snow covering the ground surface) is present for a mean of 200 days per year across the pan-Arctic, defined here as the arctic-boreal land area above 50° N. A decrease in the duration of the snow season under a warming climate represents an important feedback to climate warming. Across the pan-Arctic, and between the years 1970 and 2000, there has been a decrease in duration of approximately 2.5 days per decade of the snow season (Table 2), which translates to a 2.5 W/m^2 decade increase in absorbed energy averaged across the pan-Arctic during this same period for the snow-free season, including both changes in the time of snowmelt in the spring and first snowfall in the autumn (Fig. 2; 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 45 days from its current duration of approximately 200 days. The estimates of warming due to the radiative forcing changes from the snow–albedo feedback we present here increase linearly by 0.5% per year for a lower-end scenario, and by 1% 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 to CO_2 equivalents based on the methodology in Zhuang et al. (2006) and also in Euskirchen et al. (2010) as summarized above.

Feedbacks due to changes in methane cycling in terrestrial ecosystems.—Behavior of the Arctic methane cycle through the remainder of the 21st century is highly uncertain. Methane is present in the atmosphere in much lower concentrations than carbon dioxide, but is a more potent greenhouse gas. 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 (Forster et al. 2007). The northern circumpolar permafrost region contains 1024 Pg of organic soil carbon in the top 3 m of the permafrost (Tarnocai et al. 2009). An additional 648 Pg C is found in the deeper layers of the perennially frozen yedoma deposits (Tarnocai et al. 2009), or deposits that were formed by the deposition of sediments in unglaciated areas during glacial periods. Furthermore, the deltaic deposits, or perennially frozen deposits occurring on river deltas, contribute 241 Pg C (Tarnocai et al. 2009). This organic matter could be converted to methane and released as the climate warms and permafrost thaws (Schuur et al. 2008), resulting in methane concentrations in the atmosphere at least 300 times the current atmospheric methane concentrations. Model simulations indicate a loss of ~600 000 km^2 of permafrost by 2100 across the pan-Arctic (Euskirchen et al. 2006; Fig. 3).

Current methane emissions in the Arctic come primarily from wet soils, where methane-producing bacteria dominate. Large increases in methane emissions may occur if permafrost thaw increases dramatically, leaving a water-logged landscape that is hospitable to the methane-producing bacteria. However, the timing and rate at which this may occur is not well understood, and research suggests we have not yet triggered strong climate feedbacks from permafrost thaw (Dlugokencky et al. 2009, Kerr 2010). However, research does suggest that methane emissions have outweighed methane consumption in the terrestrial Arctic in recent years. These emissions come primarily from wetlands, and while not explicitly tied to permafrost thaw, can be tied to increases in soil temperature (Zhuang et al. 2004, Bloom et al. 2010, McGuire et al. 2010).

Currently, biogeochemical modeling estimates that the net source of methane from the Arctic terrestrial land surface is 41.5 Tg CH_4/yr, with increases by 0.5 Tg CH_4/yr between 1997 and 2006 due to a combination of biogenic (38.0 Tg CH_4/yr) and pyrogenic (3.5 Tg CH_4/yr) fluxes (McGuire et al. 2010). The biogenic emissions are primarily due to increases in methane emissions in boreal Asia under warmer soil temperatures. These emission estimates from biogeochemical modeling are comparable to those found in an atmospheric inversion of CH_4 (McGuire et al. 2010). A biogeochemical modeling study on future changes in methane in northern high latitudes estimates that the rate of increase will be 0.5 Tg CH_4/yr during the 21st century (Zhuang et al. 2006). A recent satellite-based study found increases in methane emissions in the Arctic wetlands of 1.3 Tg CH_4/yr between 2003 and 2007 (Bloom et al. 2010), accounting for a ~7% increase in global wetland CH_4 emissions. For the estimates presented here, we use the lower end of 0.5 Tg CH_4/yr for the lower set emissions, and the higher 1.3 Tg CH_4/yr for the upper end of emissions (Table 2). The methane emissions are translated into CO_2e by multiplying by 25, the global warming potential of methane over 100 years (Forster et al. 2007).

Computing the economic cost: the integrated assessment models

One metric ton of carbon dioxide emitted this year will contribute to the heating of the planet for at least the next 100 years. To arrive at a single figure summarizing the costs incurred by that ton of carbon dioxide, the so-called social cost of carbon, it is necessary to first estimate the stream of annual addi-

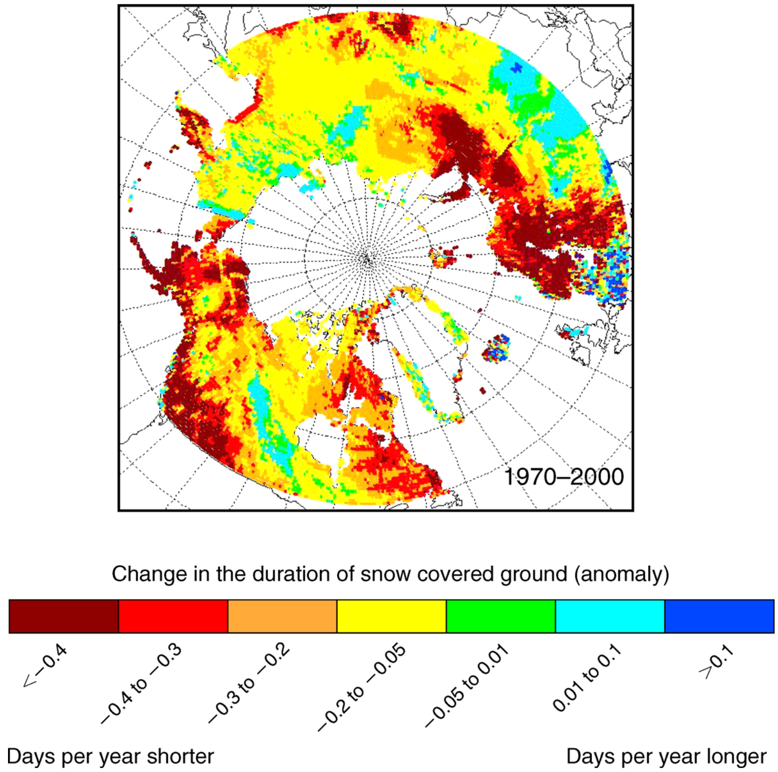

FIG. 2. Change in the duration of snow-covered ground (days per year) between 1970 and 2000. The figure is modified from Euskirchen et al. (2007)

tional costs that will be caused by the carbon, and then take the discounted net present value of that stream. This provides an estimate in today's dollars of the lifetime costs of the carbon. There are at least four major assumptions made in estimating costs that in turn will generate uncertainty in the final estimates 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. The opportunity cost of investing in carbon reduction at the expense of other productive investments.

Economists make assumptions regarding these four dimensions of the problem, and organize their analyses in the form of integrated assessment models. These models then generate estimates of the social cost of carbon, on a per metric ton CO_2 basis for a given year. These models have many limitations (Ackerman et al. 2009*a*) and as a result of omissions and simplifications are widely believed to underestimate the social cost of carbon. As noted by the IPCC (Yohe et al. 2007), "It is very likely that globally aggregated figures underestimate the damage costs because they cannot include many non- quantifiable impacts."

Table 1 illustrates the range of estimates for the social cost of carbon for 2010 that are generated by integrated assessment models, depending on the suite of underlying assumptions. The major driver of differences in the model results is the choice of discount rate. For a fuller discussion of the integrated assessment model assumptions, and in particular the impact of discounting, see Weitzman (1998), Howarth (2003, 2009), Goodstein (2007), and Goodstein et al. (2010). In Table 1, the very low, "best case" estimates assume optimistic emissions scenarios, low climate sensitivity, low estimated impacts arising from given temperature increases, and high ($\geq$5%) discount rates. Combined, these assumptions generate a social cost of carbon estimates of around \$13 per metric ton.

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 (<2%), generate the very high estimates: \$798 per metric ton in the representative case listed (Table 1), which is an EPA (2008) run of the FUND integrated assessment model. Ackerman et al. (2009*b*) generate comparably large carbon costs using the DICE integrated assessment model.

Costs of carbon estimates in this high range reflect rapid climate change, with temperature increases of up to 6°C by the end of the century. The impacts would likely encompass sea-level rise of up to 2 m, transformation of the mid- and southwestern United States into conditions of permanent drought, reductions in water supply for over one billion people in the western Americas and Asia, rapid mass extinction of a large percentage of life on earth, and so on (Solomon et al. 2007). Weitzman's (2007) reading of Solomon et al. (2007) estimates implies that the probability of this kind of worst-case outcome is on the order of 3%, and higher as we move beyond 2100.

Between these very low and very high extremes for the social cost of carbon, there are two estimates in Table 1, labeled IAWG and Stern. To assist with regulatory rule-making, the Obama Administration established an interagency working group (IAWG) to estimate values for the social cost of carbon (Interagency Working Group 2010). The agencies rely on a weighted average of published results from three integrated assessment models: FUND, DICE, and PAGE. The "central value" of the working group, assuming a 3% discount rate, was \$21 per metric ton in 2008. The estimate in Table 1 of \$22 adjusts the figure to 2008 dollars, and as explained at the end of this section, to reflect 2010 emission impacts.

In 2006, former World Bank Director Sir Nicholas Stern issued a well-known UK government report that estimated the social cost of carbon at \$87 per metric ton. Stern (2006) relied on a lower consumption discount rate (1.4%) than most previous authors, and used more inclusive temperature–damage relationships then are found, for example, in DICE and FUND (Goodstein et al. 2010). Subsequent formal modeling analyses using different major integrated assessment models reinforce the point that all integrated assessment model results are assumption driven: Stern-like assumptions generate Stern-like costs of carbon (Hope 2006, Ackerman et al. 2009*b*). The 2010 Stern estimate in Table 1 of \$104 adjusts the 2006 figure to 2008 dollars, and as explained in the next paragraph, to reflect 2010 emission impacts.

In our analysis, we utilize the two mid-range governmental estimates for 2010 that have informed official policy in the United States and UK respectively: IAWG and Stern. As we discuss elsewhere (Goodstein et al. 2010), we view the 5% discount rates that drive the low estimate in Table 1 as being inappropriate for analyses of costs a century hence. At the same time, the high end numbers, reflecting catastrophic outcomes, cannot fairly be understood unless weighed against their lower, but still significant, probability of occurrence, while also recognizing Weitzman's (2007) analysis showing that the use of expected damage estimates is problematic.

To capture the assumption of rising marginal damages, one ton of carbon emitted this year will do more damage the longer the carbon is in the atmosphere, and the wealthier is the planet, the U.S. EPA (2008), following the IPCC (Solomon et al. 2007), increases the per metric ton social cost of carbon estimates by 3% per year. We follow that procedure here for all forecasting of social cost of carbon estimates forward from the baseline year of 2010 through to 2100 (Table 3). This helps explain, as noted above, why the IAWG and Stern estimates for 2010 in Table 1 are slightly higher than for 2008 and 2006, respectively.

Results

CO_2e impacts

The upper and lower estimates for CO_2e impacts over the century due to each of the three factors analyzed here, ice albedo declines, snow albedo declines, and terrestrial methane emissions, as well as their combined impacts, are presented in Fig. 4. By 2050, the annual forcing due to sea ice albedo decline is estimated between 900 and 1800 Mg CO_2e (Fig. 4a). For sea ice, the annual forcing remains constant after 2050, under our assumptions that summer sea ice disappears after 2050 and that the annual melt is over by September. By 2100, the annual forcing due to snow albedo declines was between 1500 and 2500 Mg CO_2e (Fig. 4b). Increases in terrestrial methane emissions resulted in the largest annual forcing by 2100, ranging from 2000 to 3500 Mg CO_2e (Fig. 4c). Consequently, the combined range from these changes in sea ice, snow cover, and methane emissions is between 5000 and 8000 MT CO_2e by 2100 (Fig. 4d).

Economic costs

Fig. 5 illustrates the estimated, discounted, economic costs resulting from a thawing Arctic, for the IAWG and Stern estimates for the social cost of carbon (Tables 1 and 3), and the high and low range for increased forcing from ice and snow albedo changes and methane releases. The net present value of the annual social cost of carbon estimates underlying the costs presented in Fig. 5 use the approximate discount rate for calculating the different social cost of carbon estimates within the integrated assessment models employed: respectively, 3% for IAWG and 2% for Stern. For consistency with later comparative literature (e.g., IAWG 2010) we chose a 2% discount rate rather than a 1.4% discount rate for assessing cumulative impacts from the Stern report. This choice lowers the estimated value for our reported "high end" impacts.

The estimated global costs that will be experienced as a result of the increased planetary warming from all three sources (sea ice, snow and methane) start in the year 2010 with a range of between \$61 billion and \$371 billion (Fig. 5d). By 2100, we estimate the present value of annual damages will lie between \$102 billion and \$1.9 trillion. This annual present value cost arising from increased planetary warming breaks down as \$19 to \$448 billion from losses in sea ice (Fig. 5a), \$34 to \$650 billion from losses in snow cover, and (Fig. 5b), \$48–

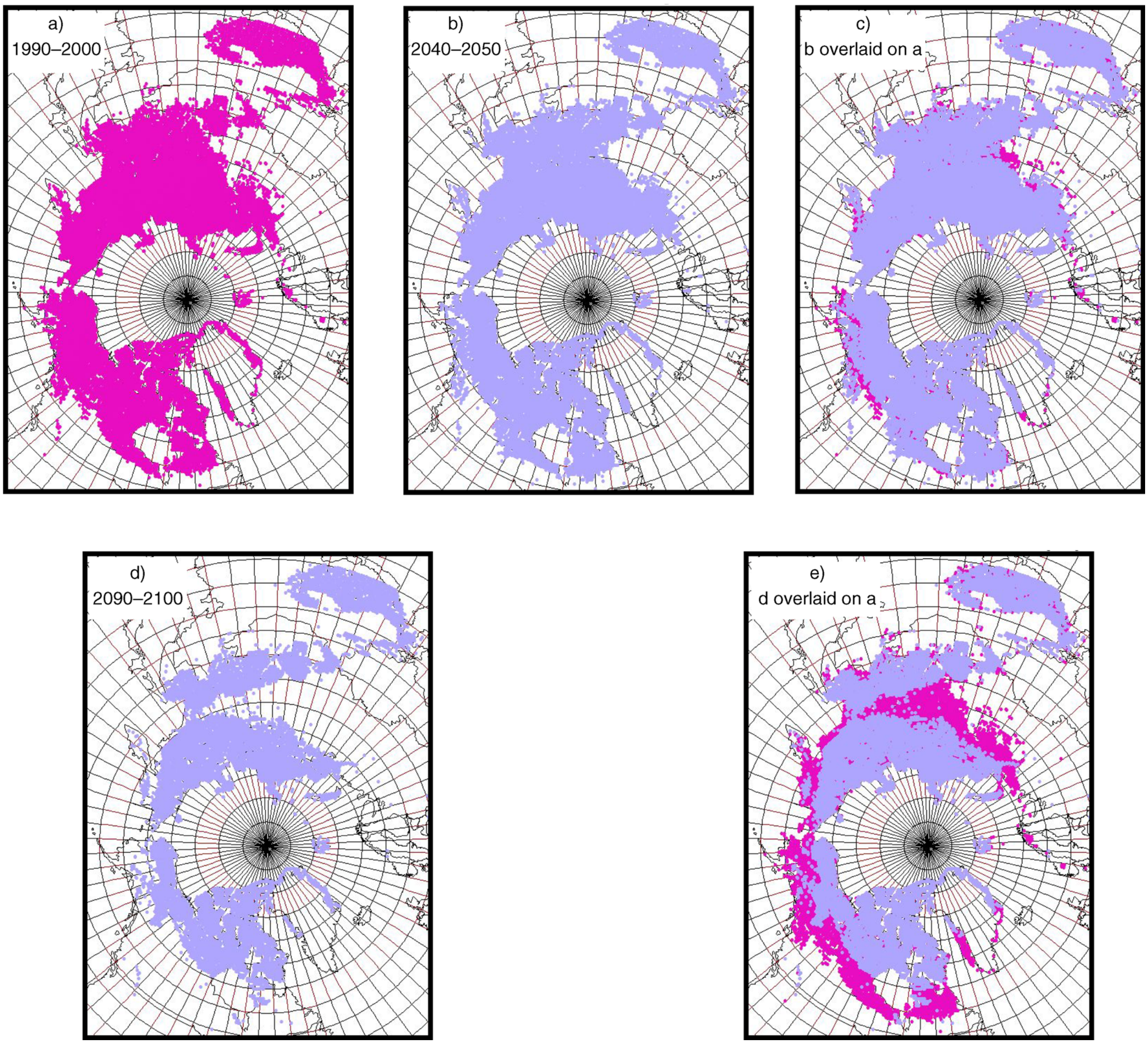

FIG. 3. The spatial distribution of (a) present-day permafrost and (b–e) possible future loss of permafrost as simulated in a large-scale terrestrial ecosystem and soil thermal model. The permafrost map in panel (a) agrees well with other permafrost maps, in particular, that of the International Permafrost Association. Data are from Euskirchen et al. (2006).

TABLE 3. Costs of lost climate services (in US$ billions, 2008) in a warming Arctic, based on computing the social cost of carbon (SCC) after the IAWG and Stern estimates given in Table 1.

	Source used for the SCC CO2e scenario (Fig. 4)			
Parameter	IAWG low	IAWG high	Stern low	Stern high
2010–2050	$2 923	$4 107	$17 078	$24 111
2010–2100	$7 546	$11 433	$59 283	$91 275
SCC	$22/Mg CO_2e	$22/Mg CO_2e	$104/Mg CO_2e	$104/Mg CO_2e
IAM discount rate	3%	3%	1.4−2.7%†	1.4−2.7%†
NPV discount rate	3%	3%	2%	2%

Note: IAM stands for integrative assessment model; NPV stands for net present value.

† Stern-like estimates can be generated using discount rates as high as 2.7%, though Stern (2006) utilized 1.4% (see Ackerman et al. 2009*b*). Following IAWG and U.S. EPA (2008), who explore the sensitivity of SCC estimates to discount rates, we utilize 3% and 2% rates to calculate the present values of future SCC estimates based on initial values from IAWG and Stern.

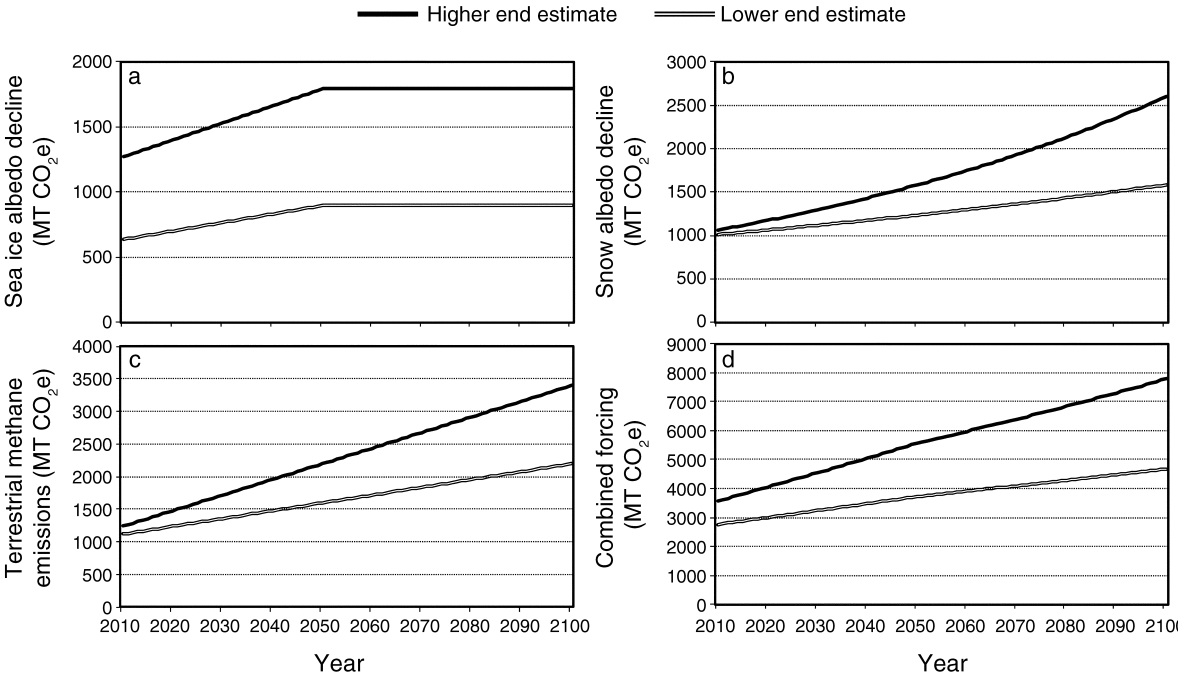

FIG. 4. Range of forcing in CO_2 equivalents (MT CO_2e) due to estimated changes in (a) summer sea ice cover, (b) the duration of the snow season, (c) changes in terrestrial methane emissions, and (d) all three forcings combined.

\$850 billion from increases in terrestrial methane emissions (Fig. 5c).

Note that the range between the low and high economic damage estimates increases, from a factor of 6 in 2010 to a factor of 20 in 2100. The initial factor 6 differential is primarily due to the different values employed for the social cost of carbon. The much larger end-of-century uncertainty results partially from the greater spread in possible forcings (which range between 4676 to 7789 Mg CO_2e in 2100; Fig. 4d), but primarily reflects the impact of differential discounting of 2% vs. 3% over the 90 year period. Also, while the costs due to changes in sea ice, snow cover, and methane emissions are nearly equally distributed in 2010, by 2100, it is evident that about half of the cost is due to increases in methane emissions (Fig. 5e). This results from the powerful forcing effect of methane, as well as the fact that our model assumes an ice-free summer Arctic by the year 2050, and thus little additional increase thereafter in Arctic Ocean albedo.

Table 3 again calculates the net present values of cumulative costs from global warming impacts using the approximate discount rate within the integrated assessment models employed: 3% and 2%, respectively. For example, in this table, the second column, labeled IAWG, uses the \$22 estimate for the social cost of carbon, the low end CO_2e forcings from Fig. 4, and discounts the stream of cumulative impacts at 3%. On the opposite end, the fifth column in Table 3, labeled Stern, uses the \$104 estimate for the social cost of carbon, the high end CO_2e forcings from Fig. 4, and discounts cumulative impacts at 2%.

By the year 2020, the estimated cumulative global costs are \$2.4 trillion, based on the mean across the scenarios (Fig. 5f). This rises to a cumulative total by 2050 of \$12 trillion, and to \$42 trillion by 2100, based on the means across the scenarios (Fig. 5f). However, there is a large range around this estimate of \$42 trillion. Notably, over the century, the cumulative economic costs are estimated to be \$91.3 trillion based on the Stern social cost of carbon and high CO_2 scenario, while the IAWG social cost of carbon and lower CO_2 scenario estimates cumulative costs of \$7.5 trillion (Table 3).

This 2100 spread in economic impacts is ~12 times larger than the emissions spread the same year. Thus the range of estimates of the present value of the social cost of carbon has a bigger impact on the results than does the range of estimates for the CO_2 equivalent forcing scenarios (Table 3, Fig. 5a–d). Again, much of the variance is being driven by the choice of discount rate, with the other assumptions discussed above playing smaller roles. Discount rate driven variance in the 2010 cost estimates results from discount rates embedded in the integrated assessment model's estimates of the initial social cost of carbon. The even wider variance in the cumulative impacts is compounded by a second round of discounting, at varying rates, to obtain the net present value of the emissions costs.

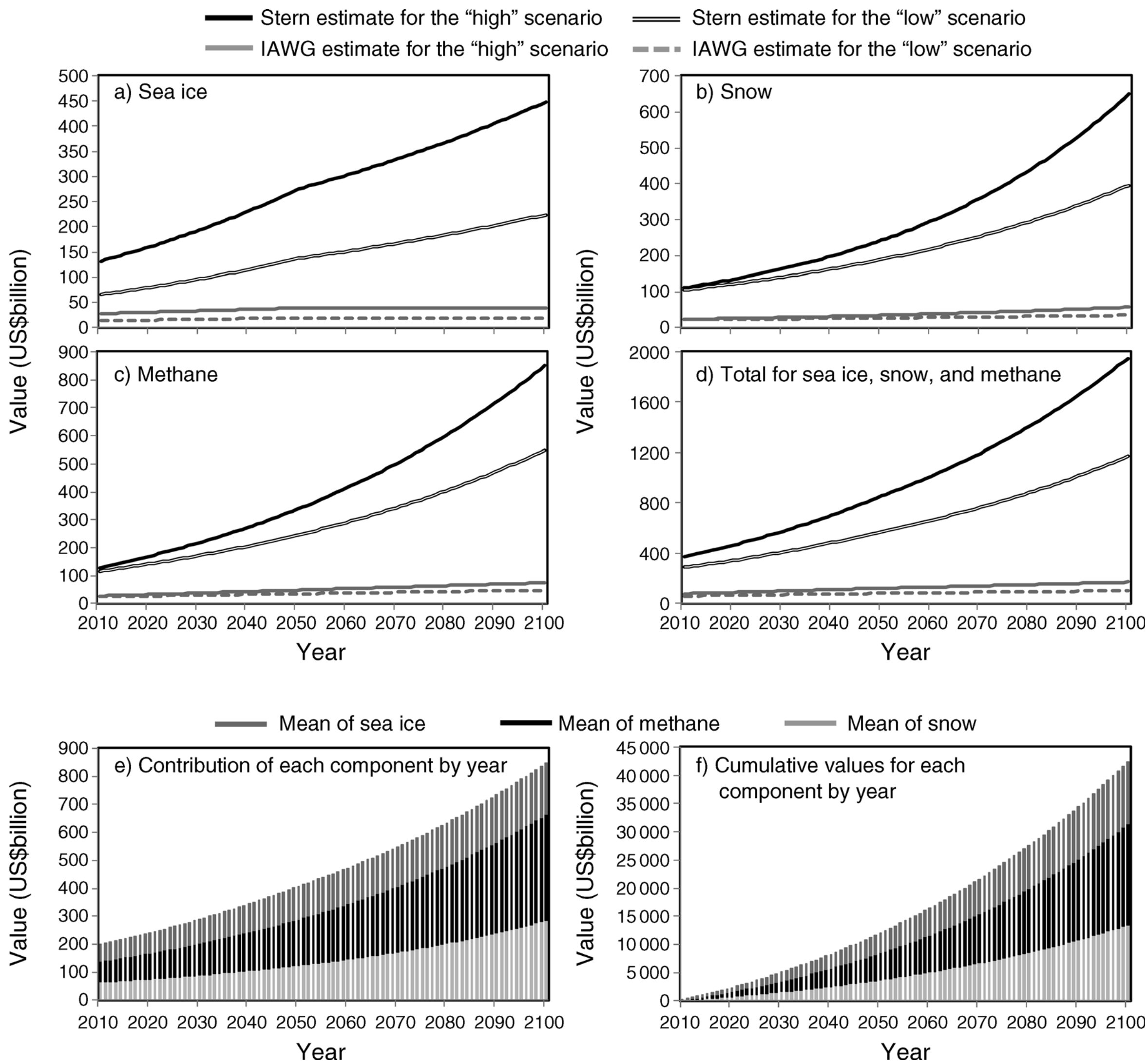

Fig. 5. Economic costs by year for each component: (a) sea ice, (b) snow, and (c) methane as well as (d) all components combined based on the high and low scenarios in Fig. 4 and estimates from IAWG (2010) and Stern (2006) social costs of carbon. (e) The annual sums of each component and (f) cumulative sums are based on the mean values of the estimates in panels (a)–(c).

Discussion

Overview

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 should be carried out. In particular, we recognize the great value that the frozen Arctic has for the people who live there, and the great range of ecosystem services 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.

Below, we consider other components related to a warming cryosphere that we did not take into account in this study, such as ice sheet and glacier loss, ocean acidification, and methane releases from the Arctic Ocean. We examine uncertainties associated with our estimates of sea ice and snow cover loss and methane emissions. We also briefly examine the analysis associated with computing the social cost of carbon.

Other global climate processes and impacts

In addition to the three processes described, changes in sea ice, snow cover, and terrestrial methane emissions, there are several other mechanisms by which the frozen Arctic affects global climate. Sea level will rise as the Greenland Ice Sheet and glaciers lose mass, a process that is underway already and may be accelerating (Dahl-

Jensen et al. 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. We do not examine methane hydrates in the Arctic Ocean since these emissions are highly uncertain (Heimann 2010). 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 (McGuire et al. 2010). The Arctic Ocean may become a stronger sink in coming decades (see *Uncertainties associated with sea ice and snow cover loss and with methane releases*), but the terrestrial environment is likely becoming a weaker sink.

The feedback mechanisms in the Arctic under a changing climate are mostly positive, and the potential negative mechanisms appear likely to be relatively small (McGuire et al. 2006). Here we are only concerned with feedback mechanisms operating in the Arctic, and not globally. Offsets outside of the Arctic are counted, at least in principle, by the social cost of carbon estimates that we employ. Furthermore, in terms of these other feedbacks to climate that operate outside of the Arctic, the positive feedbacks to warming are thought to outweigh the negative feedbacks to warming (e.g., Field et al. 2007).

Uncertainties associated with sea ice and snow cover loss and with methane releases

The general consensus in the scientific community is that summer sea ice will disappear by the middle of the 21st century, although the estimates of the timing of this disappearance differ somewhat (Holland et al. 2006). Generally, under continued climate warming, other climate feedbacks from the Arctic Ocean do not negate this positive feedback from the loss of sea. For example, large amounts of heat can accumulate in the ice-free areas of the Arctic Ocean during the short Arctic summer months of June, July, and August. However, this heat is efficiently and quickly released to the atmosphere during the following autumn, winter, and spring months, which also last much longer, from September to May. Furthermore, this additional heat source in the ocean during the summer serves to melt any remaining sea ice from below, and cause slower sea ice reformation in the fall. The sea ice that does reform is thinner, with fewer insulating properties, than the ice that was there previously, thereby permitting even greater heat loss from the ocean during the winter. That is, the additional heat storage during the summer due to a reduced area that is covered in sea ice is only temporary, whereas stable sea ice previously represented a more "permanent" reflection of heat (Screen and Simmonds 2010).

Furthermore, the Arctic Ocean will not necessarily absorb more CO_2 with decreases in sea ice. While sea ice loss will increase both nutrient and light availability in the ocean, the sea ice loss will also add freshwater to the ocean, lowering the salinity and stabilizing the surface layer. Therefore, the ocean could show a net increase in CO_2 uptake with increases in light and nutrient availability, but it may also show a decrease in net CO_2 uptake through changes in the surface layer chemistry (McGuire et al. 2009). Moreover, additional uptake of CO_2 by the ocean 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 (Steinacher et al. 2009). The balance between these different feedbacks is not clearly understood, and is therefore not included in our analysis.

Although there are important regional variations, it is also generally accepted that snow cover duration during the last three decades of the 20th century was shorter, with decreases continuing through this present century (Dye 2002, Euskirchen et al. 2007, Brown and Mote 2009, Liston and Hiemstra 2011). A recent analysis of changes in Arctic spring snow cover extent taking into account numerous data sources, including satellite observations, in situ daily snow depth observations, and reanalysis data, found that, between 1967 and 2008, May snow cover extent decreased 14% and June snow cover extent decreased 46% due to earlier melt (Brown et al. 2010). These reductions closely followed observed trends in warming and reductions in the sea ice extent, particularly in June when the albedo feedback is at a maximum (Déry and Brown 2007).

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. This includes whether a land surface becomes wetter or drier under permafrost thaw, future changes in fire regimes, thermokarst distribution (physical depressions of the ground surface), and interactions between temperature and soil moisture (Schuur et al. 2008). 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. Furthermore, longer time series of satellite data are needed in order to establish more definitive trends: the estimate for Arctic wetlands of 1.3 Tg CH_4 increase per year of Bloom et al. (2010; also see Table 2) is based on five years of data. Consequently, although there is evidence for a methane–permafrost climate feedback, the costs provided here with respect to methane are approximate since this feedback is still difficult to quantify.

Social cost of carbon estimates

Even at the low end, the economic costs presented in this study are large. This is because they reflect underlying emissions equivalents from Arctic albedo declines and increased methane releases that are currently about 42% of the total U.S. greenhouse gas emissions, and are projected to at least double in magnitude over the coming century. Consider the low-end estimate of 2010–2050 cumulative impacts: \$2.9 trillion. This is equivalent to the annual GDP of Britain or Germany. The high-end estimate is equal to the loss of all the economic output from one of these countries for ten years time. These losses in economic benefits will arise solely from the Arctic feedbacks associated with "business-as-usual" warming. Along with all of the other global benefits of greenhouse gas mitigation, the benefits of a frozen Arctic should be weighed against the cost of policies that might reduce the rate of warming, and in so doing maintain, and perhaps over the longer run, restore the Arctic's natural cooling services.

Conclusion

The frozen Arctic provides immense services to all nations by cooling the earth's temperature—the cryosphere is an air conditioner for the planet. As the Arctic thaws, 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 release of methane-hydrates from Arctic soils and ocean-beds. Rather, the purpose of this paper is to illustrate that observed changes in the Arctic snow and ice cover, and Arctic terrestrial methane releases, may already be locking in large economic costs: an estimated $61–371 billion annually (Fig. 5d). With future declines in albedo, and steady increases in methane releases both being likely, the cumulative impact over the coming decades could rise into the trillions or tens of trillions of dollars.

Some popular discussion has suggested that as the Arctic thaws, new-found treasures below the sea bed will be unlocked. In principle, any benefit from a thawing Arctic should already be captured in social cost of carbon estimates. This paper suggests that, on balance, a frozen Arctic instead 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. One important benefit of that policy goal would be a restoration of a significant portion of the climate stabilization services of the frozen Arctic identified here.

Acknowledgments

E. S. Euskirchen received funding from the National Science Foundation Office of Polar Programs in a grant to the International Arctic Research Center (OPP-0327664). We thank Scott Highleyman of the Pew Environment Group for the initial discussion that led to the ideas presented in this paper. The Pew Charitable Trusts also provided funding for the initiation of this work. We thank two anonymous reviewers for helpful comments on an earlier version of the manuscript.

Literature Cited

ACIA. 2005. Arctic climate impact assessment—scientific report. Cambridge University Press, Cambridge, UK.

Ackerman, F., S. DeCanio, R. Howarth, and K. Sheeran. 2009*a*. Limitations of integrated assessment models of climate change. Climatic Change 95:297–315.

Ackerman, F., E. A. Stanton, S. DeCanio, E. Goodstein, R. Howarth, R. Norgaard, C. Norman, and K. Sheeran. 2009*b*. The economics of 350: the benefits and costs of climate stabilization. Economics for Equity and the Environment, Portland Oregon, USA and Stockholm Environment Institute, Stockholm, Sweden.

Bloom, A. A., P. I. Palmer, A. Fraser, D. S. Reay, and C. Frankenberg. 2010. Large-scale controls of methanogenesis inferred from methane and gravity spaceborne data. Science 327:322–325.

Bony, S., et al. 2006. How well do we understand and evaluate climate change feedback processes? Journal of Climate 19:3445–3482.

Brown, R., C. Derksen, and L. Wang. 2010. A multi-data set analysis of variability and change in Arctic spring snow cover extent, 1967–2008. Journal of Geophysical Research 115:1–16.

Brown, R. D., and P. W. Mote. 2009. The response of Northern Hemisphere snow cover to a changing climate. Journal of Climate 22:2124–2145.

Cess, R. D., et al. 1993. Uncertainties in carbon dioxide radiative forcing in atmospheric general circulation models. Science 262:1252–1255.

Dahl-Jensen, D., et al. 2009. The Greenland Ice Sheet in a changing climate: snow, water, ice and permafrost in the Arctic (SWIPA). Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway.

Denman, K. L., et al. 2007. Couplings between changes in the climate system and biogeochemistry. Pages 499–587 *in* S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller, editors. Climate change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report on the Intergovernmental Panel on Climate Change. Cambridge University Press, New York, New York, USA.

Déry, S. J., and R. D. Brown. 2007. Recent Northern Hemisphere snow cover extent trends and implications for the snow-albedo feedback. Geophysical Research Letters 34:1–6.

Dlugokencky, E. J., et al. 2009. Observational constraints on recent increases in atmospheric CH_4. Geophysical Research Letters 36:1–5.

Dye, D. G. 2002. Vulnerability and trends in the annual snow-cover cycle in Northern Hemisphere land areas, 1972–2000. Hydrological Processes 16:3065–3077.

Euskirchen, E. S., A. D. McGuire, and F. S. Chapin, III. 2007. Energy feedbacks of northern high-latitude ecosystems to the climate system due to reduced snow cover during 20th century warming. Global Change Biology 13:2425–2438.

Euskirchen, E. S., A. D. McGuire, F. S. Chapin, III, and T. S. Rupp. 2010. The changing effects of Alaska boreal forests on the climate system. Canadian Journal of Forest Research 40:1336–1346.

Euskirchen, E. S., A. D. McGuire, F. S. Chapin, III, S. Yi, and C. C. Thompson. 2009. Changes in vegetation in northern Alaska under scenarios of climate change, 2003–2100: implications for climate feedbacks. Ecological Applications 19:1022–1043.

Euskirchen, E. S., et al. 2006. Importance of recent shifts in soil thermal dynamics on growing season length, productivity, and carbon sequestration in terrestrial high-latitude ecosystems. Global Change Biology 12:731–750.

Field, C. B., D. B. Lobell, H. A. Peters, and N. R. Chiariello. 2007. Feedbacks of terrestrial ecosystems to climate change. Annual Review of Ecology and Systematics 32:1–29.

Forster, P., et al. 2007. Changes in atmospheric constituents and in radiative forcing. Pages 129–234 *in* Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller, editors. Climate change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental

Panel on Climate Change. Cambridge University Press, New York, New York, USA.

Goodstein, E. 2007. Economics and the environment. Wiley, Hoboken, New Jersey, USA.

Goodstein, E., E. S. Euskirchen, and H. Huntington. 2010. An initial estimate of the cost of lost climate regulation services due to changes in the Arctic cryosphere. Pew Environment Group, Washington, D.C., USA.

Heimann, H. 2010. How stable is the methane cycle? Science 327:1211–1212.

Holland, M. M., C. M. Bitz, and B. Tremblay. 2006. Future abrupt reductions in the summer Arctic sea ice. Geophysical Research Letters 33:1–5.

Hope. C. 2006. The social cost of carbon: what does it actually depend on? Climate Policy 6:565–572.

Howarth, R. 2003. Discounting and uncertainty in climate change policy analysis. Land Economics 79:369–381.

Howarth, R. 2009. Discounting, uncertainty, and revealed time preference. Land Economics 85:24–40.

Interagency Working Group. 2010. Social cost of carbon for regulatory impact analysis under Executive Order 12866. Whitehouse Council of Economic Advisors, Washington, D.C., USA.

Kerr, R. A. 2010. "Arctic Armageddon" needs more science, less hype. Science 329:620–621.

Lawrence, D. M., A. G. Slater, R. A. Tomas, M. M. Holland, and C. Deser. 2008. Accelerated Arctic land warming and permafrost degradation during rapid sea ice loss. Geophysical Research Letters 35:1–6.

Light, B., T. C. Grenfell, and D. K. Perovich. 2008. Transmission and absorbtion of solar radiation by Arctic sea ice during the melt season. Journal of Geophysical Research 113:C03023. http://dx.doi.org/10.1029/2006JC003977

Liston, G. E., and C. A. Hiemstra. 2011. The changing cryosphere: pan-Arctic snow trends (1979–2009). Journal of Climate 24:5691–5712.

Lutgens, F. K., E. J. Tarbuck, and D. Tasa. 2008. Essentials of geology. 10th edition. Prentice Hall, New York, New York, USA.

Maslanik, J. A., C. Fowler, J. Stroeve, S. Drobot, J. Zwally, D. Yi, and W. Emery. 2007. A younger, thinner Arctic ice cover: Increased potential for rapid, extensive sea-ice loss. Geophysical Research Letters 34:1–5.

McGuire, A. D., L. G. Anderson, T. R. Christensen, S. Dallimore, L. Guo, D. J. Hayes, M. Heimann, T. D. Lorenson, R. W. Macdonald, and N. Roulet. 2009. Sensitivity of the carbon cycle in the Arctic to climate change. Ecological Monographs 79:523–555.

McGuire, A. D., F. S. Chapin, III, J. E. Walsh, and C. Wirth. 2006. Integrated regional changes in Arctic climate feedbacks: implications for the global climate system. Annual Review of Environment and Resources 31:61–91.

McGuire, A. D., et al. 2010. An analysis of the carbon balance of the Arctic Basin from 1997–2006. Tellus 62B:455–474.

Pedersen, C. A., E. Roeckner, M. Lüthje, and J.-G. Winther. 2009. A new sea ice albedo scheme including melt ponds for ECHAM5 general circulation model. Journal of Geophysical Research 114:1–15.

Polyakov, I. D., G. V. Alekseev, R. V. Bekryaev, U. Bhatt, R. Colony, M. A. Johnson, V. P. Karklin, A. P. Makshtas, D. Walsh, and A. V. Yulin. 2002. Observationally based assessment of polar amplification of global warming. Geophysical Research Letters 29:1–4.I.C.

Prentice, I. C. et al. 2001. The carbon cycle and atmospheric carbon dioxide. Pages 188–237 *in* J. T. Houghton, Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell, and C. A. Johnson, editors. Climate change 2001: the scientific basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.

Rind, D., R. Healy, C. Parkinson, and D. Martinson. 1995. The role of sea ice in 2×CO_2 climate model sensitivity. Part I: The total influence of sea ice thickness and extent. Journal of Climate 8:449–463.

Schuur, E. A. G., et al. 2008. Vulnerability of permafrost carbon to climate change: implications for the global carbon cycle. BioScience 58:701–714.

Screen, J. A., and I. Simmonds. 2010. The central role of diminishing sea ice in recent Arctic temperature amplification. Nature 464:1334–1337.

Serreze, M. C., and J. A. Francis. 2006. The Arctic amplification debate. Climatic Change 76:241–264.

Solomon, S., D. Qin , M. Manning , Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller, editors. 2007. Climate change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, New York, New York, USA.

Steinacher, M., F. Joos, T. L. Frolciher, G.-K. Plattner, and S. C. Doney. 2009. Imminent ocean acidification in the Arctic projected with the NCAR global coupled carbon cycle-climate model. Biogeosciences 6:515–533.

Stern, N. H. 2006. The economics of climate change. Cambridge University Press, Oxford, UK.

Stroeve, J., M. M. Holland, W. Meier, T. Scambos, and M. Serreze. 2007. Arctic sea ice decline: faster than forecast. Geophysical Research Letters 34:1–5.

Tarnocai, C., J. G. Canadell, E. A. G. Schuur, P. Kuhry, G. Mazhitova, and S. Zimov. 2009. Soil organic carbon pools in the northern circumpolar permafrost region. Global Biogeochemical Cycles 23:1–11.

Tol, R. 2008. The social cost of carbon: trends, outliers and catastrophes. Economics 2:1–22.

U.S. EPA. 2008. Technical support document on benefits of reducing GHG emissions. U.S. Environmental Protection Agency, Washington, D.C., USA.

U.S. EPA and NHTSA (National Highway Traffic Safety Administration). 2009. Proposed rulemaking to establish light-duty vehicle greenhouse gas emission standards and corporate average fuel economy standards. Docket No. EPA–HQ–OAR–2009–0472/NHTSA–2009–0059. Federal Register 74(186).

Weitzman, M. 1998. Why the far-distant future should be discounted at its lowest possible rate. Journal of Environmental Economics and Management 36:201–208.

Weitzman, M. 2007. A review of "The Stern Review on the Economics of Climate Change." Journal of Economic Literature 45:703–724.

Yohe, G. W., R. D. Lasco, Q. K. Ahmad, N. W. Arnell, S. J. Cohen, C. Hope, A. C. Janetos, and R. T. Perez. 2007. Perspectives on climate change and sustainability. Pages 811–841 *in* M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden, and C. E. Hanson, editors. Climate change 2007: impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.

Zhuang, Q., J. M. Melillo, D. W. Kicklighter, R. G. Prinn, A. D. McGuire, P. A. Steudler, B. S. Felzer, and S. Hu. 2004. Methane fluxes between terrestrial ecosystems and the atmosphere at northern high latitudes during the past century: a retrospective analysis with a process-based biogeochemistry model. Global Biogeochemical Cycles 18:1–23.

Zhuang, Q., J. M. Melillo, M. C. Sarofin, D. W. Kicklighter, A. D. McGuire, B. S. Felzer, A. Sokolov, R. G. Prinn, P. A. Steudler, and S. Hu. 2006. CO_2 and CH_4 exchanges between land ecosystems and the atmosphere in northern high latitudes over the 21st Century. Geophysical Research Letters 33:1–5.