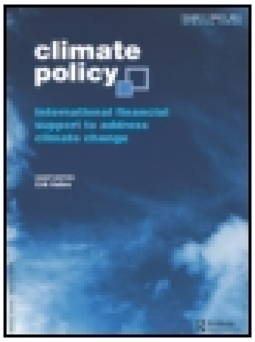

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research article

Using the social cost of carbon to value earth observing systems

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The goal of this study is to show how to quantify the benefits of accelerated learning about key parameters of the climatic system and use this knowledge to improve decision-making on climate policy. The US social cost of carbon (SCC) methodology is used in innovative ways to value new Earth observing systems (EOSs). The study departs from the strict US SCC methodology, and from previous work, in that net benefits are used instead of only damages to calculate the value of information of the enhanced systems. In other respects the US SCC methodology is followed closely. We compute the surfeit expected net benefits of learning the actionable information earlier, with the enhanced system, versus learning later with existing systems. The enhanced systems are designed to give reliable information about climate sensitivity on accelerated timescales relative to existing systems; therefore, the decision context stipulates that a global reduced emissions path would be deployed upon receiving suitable information on the rate of temperature rise with a suitable level of confidence. By placing the enhanced observing system in a decision context, the SCC enables valuing this system as a real option.

Policy relevance

Uncertainty in key parameters of the climatic system is often cited as a barrier for near-term reductions of carbon emissions. It is a truism among risk managers that uncertainty costs money, and its reduction has economic value. Advancing policy making under uncertainty requires valuing the reduction in uncertainty. Using CLARREO, a new proposed EOS,as an example, this article applies value of information/real option theory to value the reduction of uncertainty in the decadal rate of temperature rise. The US interagency social cost of carbon directive provides the decision context for the valuations. It is shown that the real option value of the uncertainty reduction, relative to existing observing systems, is a very large multiple of the new system's cost.

Keywords: CLARREO; climate observing system; DICE; real option value; social cost of carbon; value of information

1. Introduction

Uncertainty in key parameters of the climatic system is often cited as a barrier for near-term carbon emissions reduction. It is known among risk managers that uncertainty costs money, thus there is economic value in reducing uncertainty. Progress in policy making under uncertainty requires valuing these reduction in uncertainty. The article presents application of the real options methodology for economic valuation of the enhanced EOS, calculated as the avoided cost of climate policy, both in global damages and abatement costs.

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In the past, designers of EOSs have labored under the constraint that the costs of such missions were justified solely on the basis of increasing our knowledge base, and not on the monetized social value of that knowledge. A policy environment that places a low value on scientific knowledge will therefore run the risk of foregoing the social value that such knowledge may confer. The carbon accounting methodology laid down by the Interagency Working Group on Social Cost of Carbon [IWG SCC], 2010 (hereafter SCC), although designed for regulation (Kopp and Mignone, 2012), provides a mechanism for monetizing the social value of new knowledge, at least with regards to climate change.

We use the results of Wielicki et al. (2013) for the Climate Absolute Radiance and Refractivity Observatory (CLARREO) space-based mission as an illustration. Establishing a climate trend involves observing a timeseries long enough to distinguish the trend, with requisite certainty, from natural variability, calibration drift, and instrument error. CLARREO was recommended by the US National Academies as a Decadal Survey mission because it addressed one of the most critical issues for current climate observations – their lack of accuracy. CLARREO's improved accuracy could achieve a requisite level of certainty for climate trends from a shorter timeseries. In particular, CLARREO could deliver the requisite certainty about the decadal rate of temperature rise from a shorter timeseries than existing satellite observing systems, denoted I/A/C (for IASI, AIRS, CrIS, see Cooke, Wielicki, Young, & Mlynczak, 2013 for further explanation). If we assume that a high decadal rate of temperature rise triggers a shift to an appropriately modified climate policy, then learning this fact sooner rather than later could be of considerable value. Similarly, learning a low decadal rate of temperature rise with requisite certainty earlier rather than later could avoid expensive and unnecessary mitigation measures. In short, an improved accuracy EOSs creates an option for using new information for adoption of climate policy based on better knowledge about the climatic system. Learning about climate is not without costs. Accordingly, the value of a more accurate EOS should be assessed as its 'real option value', that is, the value of the information it provides, within a given decision context, relative to existing systems.

Calculation of a value of information (VOI), presented in Cooke et al. (2013), represents a good initial estimate but there are several areas where the calculation could be improved, albeit at the expense of some fidelity to the SCC methodology. These recommended enhancements include: (1) accounting for more uncertainty regarding climate and economic variables; (2) incorporating a decreasing discount rate over time, as advocated in (Arrow et al., 2013); (3) using an abatement cost function instead of a production shock, thereby basing the VOI on the net benefits of a reduced emissions policy rather than averted damages; and (4) calculating the 'real option value' of the improved EOS. Whereas the VOI calculations hardwired our future actions upon observing the trigger value, real option theory values the new EOS as an option to make optimal future choices. Of these four possible enhancements, the first is quite feasible, but awaits defensible quantifications of other uncertainties. The second recommendation is also feasible, but in the absence of a commonly agreed discount rate path, the authors have chosen to keep the effect of the discount rate visible by retaining the SCC rates. The third recommendation is feasible and is undertaken here[1]. The fourth recommendation would require choosing an optimal emissions path based on our updated distribution of the climate uncertainty after observing the trigger value with requisite confidence. The stochastic optimization problem is challenging, and would become much more challenging under a more realistic uncertainty accounting. However, we can take a significant step toward implementing item (4) by letting the choice among the pre-selected emission scenarios depend on the posterior uncertainty in the value of climate sensitivity after observing the trigger value.

In this article we relax the previous assumption about prescribed policy choice. Society now chooses the best climate policy from a fixed choice set, given the revealed climate sensitivity at the time. The choice set of climate policies is {BAU (business as usual), DICE optimal emissions path, 2.5 °C stabilization path and Stern emissions path}.[2] When a trigger value is observed, society chooses the reduced emissions path with the best net benefits. The real option value of the new EOS is the difference in expected net benefits realized by triggering on the new versus the current EOS. Under discount rates of 2.5%, 3% and 5% the option value of the new EOS is 16.70, 9.00 and US$ 1.07 trillion (2008) respectively. The policy choices that realize these benefits depend on the discount rate and the time of triggering[3].

While the current study uses CLARREO as an example of a higher accuracy EOS, with a single decision trigger climate variable (temperature), the method is generally applicable to a wide range of climate observations as well as to decisions based on multiple climate signals.

This article is organized as follows: Section 2 discusses climate uncertainty and importance of EOS improvements, Section 3 discusses a trigger value for climate policy, Section 4 outlines the decision context for the VOI calculations, Section 5 compares averted damages, net benefits and benefit–cost ratios, Section 6 presents results, and Section 7 introduces the real option value.

2. Uncertainty reduction

Specific unanswered scientific questions with large impacts on societal costs include uncertainty in the rate of sea-level rise from melting of the major ice sheets in Greenland and Antarctica, uncertainty in climate sensitivity including cloud and carbon cycle feedbacks, uncertainty in anthropogenic aerosol radiative forcing, and uncertainty in future ocean acidification (IPCC, 2007). This list is not exhaustive, but serves to demonstrate the diversity of climate science challenges. Meeting these challenges requires both improved observations as well as improved climate system predictive models. More accurate climate predictions, validated by improved observations, can then provide the basis for more cost-effective climate policies.

In addition to the noise of natural variability, climate trend uncertainty can also be increased by uncertainties in the climate observing system. One of the largest sources of observing system uncertainty is the changing calibration of satellite instruments over time (Karl, Hassol, Miller, & Murray, 2006; Leroy, Anderson, & Ohring, 2008; Trenberth et al., 2013). This can be caused either by slow drifts of instrument calibration over years in orbit, or by differences in absolute calibration between successive instruments that either cannot be fully removed during overlap time periods, or cannot be removed because of a time gap between the end of one observation and the start of its replacement. A second major source of observing system uncertainty is sampling error, which can be caused if the orbit has limited space/time coverage or has systematic drifts in local time of day sampling for satellite instruments (IPCC, 2007; Karl et al., 2006).

We can combine the sources of uncertainty in climate trends to determine the total uncertainty in a decadal measurement trend[4] $\sigma_m(\Delta t)$ based on observation period Δt as (see Leroy et al. (2008), the Supplementary Online Material of Cooke et al. (2013) contains a derivation):

$$(\sigma_m(\Delta t))^2 = 12(\Delta t)^{-3}(\sigma_{\mathrm{var}}^2\tau_{\mathrm{var}} + \sigma_{\mathrm{cal}}^2\tau_{\mathrm{cal}} + \sigma_{\mathrm{orbit}}^2\tau_{\mathrm{orbit}}) \tag{1}$$

where Δt is the length of observation period in years, σ^2_{var} is the variance of natural variability and τ_{var} is the autocorrelation time scale of natural variability. Roughly, the autocorrelation accounts for the fact that successive measurements are not independent, so the sum square error has to account for the effective number of independent observations. The more serially correlated the observations, the larger τ is and the greater the uncertainty after observing the process for time Δt. Calibration uncertainty σ^2_{cal} and satellite orbit sampling uncertainty σ^2_{orbit} are treated similarly. Eq (1) is general enough to be used for any climate variable of interest such as temperature, water vapor, cloud height, sea level, or for remote sensing observations of radiance, reflectance, or brightness temperature. In each case, the variable chosen determines the units of σ^2_{m}, σ^2_{var}, σ^2_{cal}, and σ^2_{orbit}. For this study, the values for these quantities are taken from Cooke et al. (2013), to which the reader is referred for details. A measurement is termed 'perfect' if there is no measurement error, and only uncertainty from natural variability is in play.

3. Trigger value: when is learning 'completed'?

The CLARREO improved EOS helps to reduce uncertainties to acceptable levels in a shorter time than existing observing systems. A trigger variable $\Delta\,(CS, E(t))$ depending on the unknown climate sensitivity (CS) and the emissions path $E(t)$ as function of time is chosen. In our case $\Delta(CS, E(t))$ is the decadal rate of temperature rise. Under the operative assumptions of the SCC, this rate is uniquely determined by CS and $E(t)$. We observe this rate over a period of Δt, denoting the observed value $\Delta_{\text{obs}(\Delta t)}$. The uncertainty in $\Delta_{\text{obs}(\Delta t)}$, as given in eq (1), is assumed to follow a normal distribution:

$$\Delta_{\text{obs}(\Delta t)} - \Delta(CS, E(t)) \sim Z \times 10 \times \sigma_m(\Delta t),$$

where Z is a standard normal variable, and the factor 10 converts the yearly rate of (eq 10) to a decadal rate. Hence, to be 95% certain that the true value $\Delta(CS, E(t))$ exceeds 0.2 °C per decade, we must have $\Delta_{\text{obs}(\Delta t)} > 1.65 \times 10 \times \sigma_m(\Delta t) + 0.2$. More generally, if we choose a trigger value δ and a corresponding uncertainty level Z_δ, then we 'pull the trigger' when

$$\Delta_{\text{obs}(\delta t)} > 10 \times Z_\delta \times \sigma_m(\Delta t) + \delta \tag{2}$$

Note that $\sigma_m(\Delta t)$ decreases with the 3/2 power of Δt. Hence, for observational period Δt sufficiently large, we will eventually pull the trigger provided $\delta \leq \Delta(CS, E(t))$. Reducing $(\sigma^2_{\text{var}}\tau_{\text{var}} + \sigma^2_{\text{cal}}\tau_{\text{cal}} + \sigma^2_{\text{orbit}}\tau_{\text{orbit}})$ means that we will pull the trigger sooner. When the trigger value of the chosen variable is exceeded with the required confidence, we switch from the BAU path to an alternative path, which may be any of the other paths listed in Table 1.

The function $\Delta(CS, E(t))$ is determined using the DICE Integrated Assessment Model as a function of equilibrium CS and the time varying emissions scenario $E(t)$ as shown in Table 2 and Figure 1. The choices of trigger variable, trigger value and requisite confidence level are policy choices.

We use 2020 as the starting date for the decision trigger, despite the fact that the AIRS instrument launched in 2002. The reason for this decision is that the use of current temperature change observations to limit uncertainty in CS is severely limited by the factor of 3 uncertainty in total

TABLE 1 Total carbon emissions per year through 2115 for each of the four scenarios used in the VOI calculations (Nordhaus, 2008).

Total carbon emissions (GtC per year)											
	2015	2025	2035	2045	2055	2065	2075	2085	2095	2105	2115
BAU	10.463	12.395	14.566	16.741	18.716	20.388	21.699	22.593	23.158	23.361	22.640
DICE Opt	8.956	9.994	10.838	11.227	11.027	10.222	8.887	7.149	5.154	3.044	0.932
Lim2.5C	8.897	9.868	10.576	10.716	10.106	8.702	6.601	4.079	1.684	0.541	0.401
Stern	5.200	4.974	4.653	4.211	3.630	2.878	1.951	0.805	0.148	0.118	0.0945

TABLE 2 Damages in 2008 US international dollars (trillions) per year associated with the specified global surface air temperature warming above pre-industrial levels. Damages and temperature warming are shown for each of the scenarios used in the VOI calculations (Nordhaus, 2008).

Climate sensitivity = 3 C											
	2015	2025	2035	2045	2055	2065	2075	2085	2095	2105	2115
BAU dam	0.244	0.556	1.173	2.279	4.079	6.773	10.508	15.352	21.285	28.199	35.783
BAU temp	0.947	1.198	1.477	1.781	2.102	2.433	2.766	3.093	3.410	3.711	3.986
DICE dam	0.202	0.417	0.774	1.283	1.898	2.507	2.950	3.068	2.730	1.902	0.641
DICE temp	0.938	1.164	1.401	1.642	1.879	2.101	2.300	2.468	2.600	2.692	2.735
lim 2.5 dam	0.200	0.410	0.750	1.209	1.702	2.058	2.066	1.592	0.752	0.238	0.197
lim 2.5 temp	0.938	1.162	1.397	1.633	1.861	2.068	2.243	2.376	2.461	2.500	2.500
Stern dam	0.103	0.166	0.237	0.305	0.353	0.357	0.291	0.124	0.000	0.000	0.000
Stern temp	0.916	1.081	1.226	1.353	1.461	1.549	1.616	1.658	1.676	1.676	1.661

anthropogenic radiative forcing, an uncertainty caused primarily by uncertain changes in aerosol radiative forcing (IPCC, 2013). We assume for this study that by 2020 a new observation or methodology to greatly reduce the uncertainty in aerosol forcing (natural and anthropogenic) is available for use in observation studies in 2020 and beyond.

Figure 1 shows the temperature paths under the BAU emissions scenario, as a function of *CS*, as predicted by the DICE model. From this picture one might conclude that one could infer *CS* from accurate measures of global mean temperature. However, Figure 1 does not take natural variability, orbital decay and calibration error into account.

CLARREO is designed to learn the decadal rate of temperature rise faster than would be possible with existing global satellite observations. Having this information sooner can lead to more informed and timelier decisions about climate change policies.

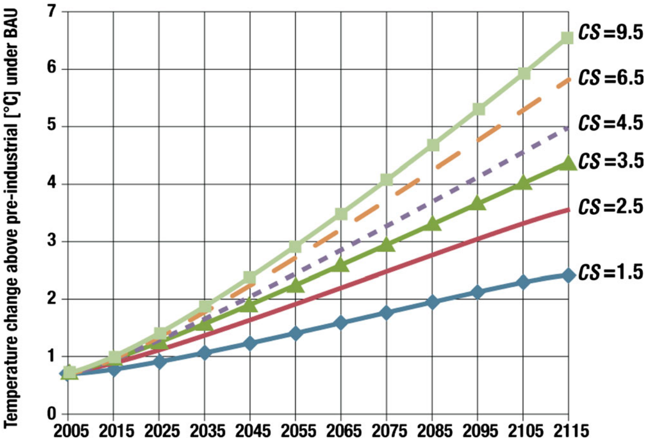

FIGURE 1 DICE temperature paths under BAU as function of climate sensitivity.

4. Decision context for VOI calculations

This section describes the VOI calculations in (Cooke et al., 2013), and contrasts with the real option value calculations described in section 7. Following the SCC, Cooke et al. (2013) monetized this accelerated learning as expected averted damages by introducing a decision context in which this information is used to alter our emissions path. Four emissions paths define the decision context (see Table 1):

- BAU
- DICE Optimal path (the path equating marginal climate damages and marginal abatement costs, assuming $CS = 3$ °C)
- A path stabilizing global temperature rise above the pre-industrial level (Lim2.5 °C, assuming $CS = 3$ °C)[5]
- Stern Report emissions path[6]

Damages and temperatures for all four emissions scenarios assuming an equilibrium CS of 3 °C for doubled CO_2 are shown in Table 2. Emissions and damages are extended out to 2205, though only the initial 2005–2115 are shown in Table 2.

Although the SCC applied three different models for numerical analysis, we selected DICE. The enormous advantage of using DICE is that it is accessible and very well documented. DICE was run exactly as the SCC stipulates, with a truncated Roe Baker distribution on CS. Using the DICE carbon cycle and impact of CO_2 concentrations on mean global temperature, the distribution of CS leads to a distribution of temperature paths. If we could observe the global mean temperature without uncertainty at two time points then, under the DICE modelling assumptions, we could infer the unique value of CS that intersected these points. However, we cannot observe global mean temperature with certainty. Natural variability of the Earth climate system always adds some noise. Therefore we must observe a sequence of mean global temperature measurements over time. The longer the sequence of observations, the more certain we become about the decadal rate of mean global temperature rise. In fact the standard deviation of the uncertainty on the rate of temperature rise decreases with the 3/2 power of the length of the observation period (eq 1). Natural variability is inescapable, but our observations are also affected by uncertainty from our observing system. By reducing measurement uncertainty we can reduce the time required to measure a trend with requisite certainty.

CLARREO doesn't give climate projections as such, it enables global mean temperature to be measured with smaller uncertainty than the existing satellite systems. Hence the time required to attain requisite certainty over decadal temperature rise (and hence over *CS*) is shorter than with existing measurement systems. This shortened learning horizon enables swifter reaction to 'bad news' about *CS*. This swifter reaction leads to lower climate damages and lower abatement costs.

The decision context used to calculate the VOI is as follows. It is assumed that we begin on the BAU path. Then as policy makers determine that the rate of warming is too high (i.e. (2) holds) society switches to one of emissions pathways described in Table 1. Each EOS (CLARREO or existing I/A/C) will ring a bell ('pull the trigger') when it is 95% confident that the decadal rate of temperature rise is at least 0.2 °C per decade. When the trigger is pulled depends on the (unknown) value of *CS*, and on the accuracy of the EOS. Whichever system is in use, when the bell is rung, society computes the expected net benefits of the four emissions policies and chooses the policy with the greatest expected net benefits.

We then compute the expected climate damages along the altered emissions paths. The difference between BAU damages and damages on the altered path is the averted damages. Upon choosing a discount rate, the present value of averted damages is then computed.

Following the SCC the VOI computed in Cooke et al. (2013) was based only on damages. The calculation algorithm is summarized as follows:

(1) Draw a value of *CS* from the Roe Baker distribution.
(2) For this *CS*, compute the time at which CLARREO and I/A/C would pull the trigger (these are two distinct time points).
(3) At each of these two time points compute the net present value (NPV) under each of the three discount rates of averted damages for the three reduced emissions policies.
(4) Compute the difference in averted damages CLARREO – I/A/C, per emissions path
(5) Multiply this number by the probability of observing *CS*.
(6) Repeat (1)–(5) and add results to compute the VOI for CLARREO relative to I/A/C

This VOI depends on when the CLARREO mission is launched, the trigger value, the required confidence and the reduced emissions path to which society switches. Note that the time to detect the trigger value and the damages depend on the (uncertain) *CS* parameter. The decision context is summarized in Table 3.

Cooke et al. (2013) studied the sensitivity of the damage based VOI calculation to the launch date, trigger value and confidence level used in Table 3, finding modest changes of 20 to 30%. While total economic impacts changed with those values, the relative value of earlier triggering was much less sensitive. The lost VOI per year of delay (US$ 250 billion) is about 30 times larger than the cost of increasing

TABLE 3 Decision context– trade space of options.

Trigger variable	Global temperature change/decade		
Trigger value δ	Free choice		
Confidence level Z_δ	Free choice		
CLARREO launch date	Assume initial launch in 2020 and recurring launches every 5 years		
Altered emissions policy: switch from BAU to:	DICE Opt	Lim 2.5°C	Stern
Discount rate	2.5%	3%	5%

current global investments in climate observations by a factor of 3 (Cooke et al., 2013). Discount rates have a large impact on VOI.

5. Damages versus net benefits

This study departs from the SCC in focusing on the expected net benefits of the enhanced CLARREO EOS instead of expected averted damages. Expected net benefits are computed as follows:

Expected net benefits CLARREO enhanced EOS = Expected (Damages BAU + Abatement costs of BAU) – Expected (Damages reduced emissions path + Abatement costs of reduced emissions path).

The surfeit expected net benefits of the enhanced EOS relative to the existing system I/A/C is then:

Expected net benefits of CLARREO Enhanced EOS – Expected net benefits of I/A/C.

The benefit–cost ratio ('bang for your buck') is sometimes used as an indicator. In the present context where benefits are averted damages, this is:

Expected benefit–cost ratio = Expectation (Damages of BAU – Damages reduced emissions path) / Abatement costs reduced emissions).

To get an idea of the total abatement costs, Figure 2 shows the present value of abatement costs for the CLARREO enhanced EOS and I/A/C as function of *CS* for various decision parameters. These costs increase dramatically as the reduced emissions path shifts from DICE Optimal to Lim 2.5 °C to Stern – transitioning from gradual to more aggressive emission reduction targets. Note that CLARREO is always a bit higher than I/A/C since CLARREO triggers earlier and thus abates more.

Abatement costs depend on *CS*, discount rate and choice of EOS.

As discounting lowers the present value of damages, it also lowers the present value of abatement costs. Climate sensitivity plays an essential role in selection of climate policy. Higher *CS* requires more drastic and therefore more expensive interventions.

6. Results

Table 4 shows the expected net benefits for the three reduced emissions scenarios when the policy switch is triggered by CLARREO and by I/A/C. Accounting for abatement costs lowers the differences between the enhanced EOS and I/A/C. Whereas the expected averted damages for the DICE Optimal

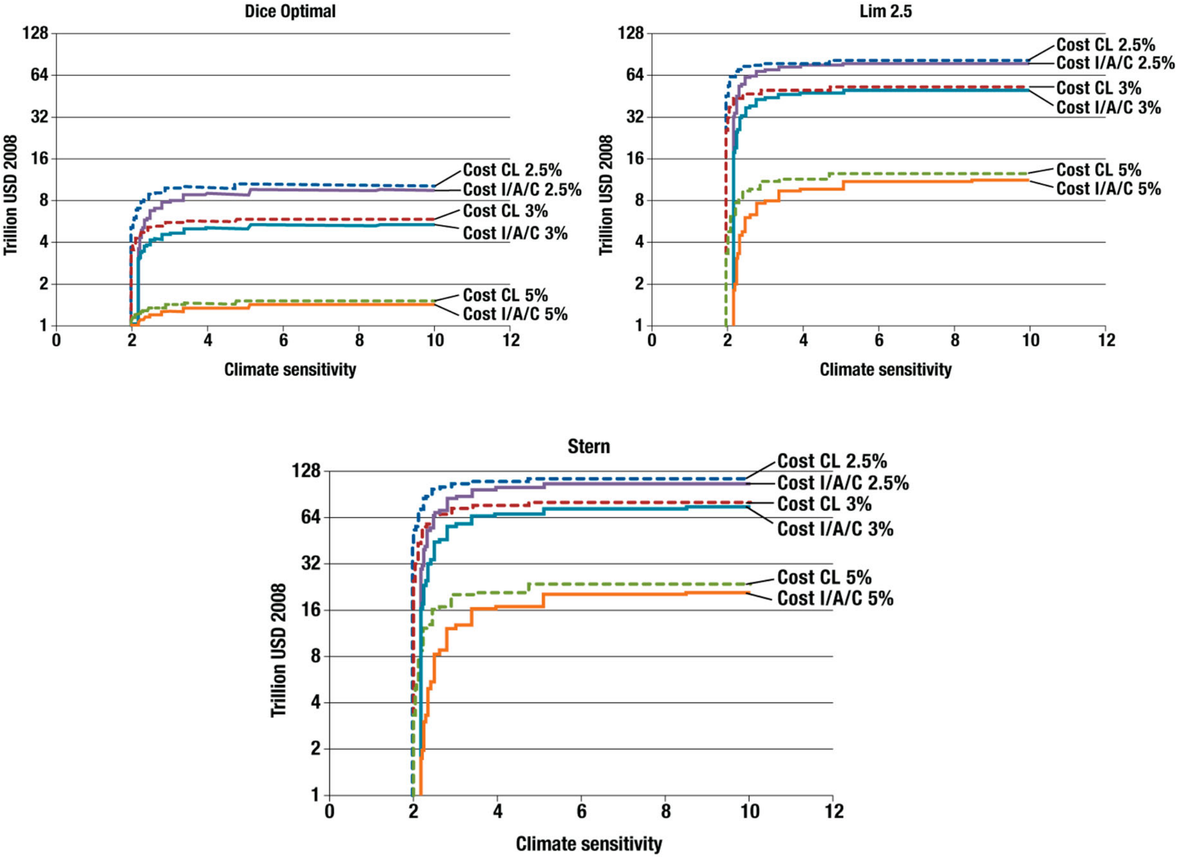

FIGURE 2 Present value of abatement costs for CLARREO (CL) and I/A/C, launch date 2020, switch to DICE optimal (upper left) Lim 2.5 °C (upper right) or Stern (lower) policy on 0.2 °C per decade trigger with 95% confidence for discounts rate of 2.5%, 3%, and 5%.

path are US$ 17.55, 11.67 and 3.14 trillion (2008) (Cooke et al., 2013), the surfeit expected net benefits are US$ 9.894, 5.933 and 0.988 trillion (2008) for discount rates 2.5%, 3% and 5% respectively.

Significantly, the surfeit expected net benefit when switching to the Stern path at the 5% discount rate is actually negative. Put ironically, it is better to make a bad decision later rather than earlier. This paradoxical outcome is explained by the fact that at 5% discounting, the expected NPV of abatement costs are higher than the expected NPV of the averted climate damages, which accrue later than the abatement costs.

In all cases, excluding the Stern path at a discount rate of 5%, the expected net benefits of the adopting a climate policy based on CLARREO information are higher than the net benefits of adopting a climate policy based on I/A/C. Switching to the Lim 2.5 °C path has substantially greater expected net benefits than the other two emissions policies for discount rates 2.5% and 3%, and is ‘competitive’ with DICE optimal at 5% (see values in bold). The earlier study (Cooke et al., 2013) tested the sensitivity

TABLE 4 Expected net benefits of CLARREO and I/A/C in the base case in 2008 US international dollars (trillions).

Net Benefits: E(BAU (Damage + Cost) − Red Em(Damage + Cost)				
Base Case: Tigger = 0.2 °C per decade; sigma = 1.65 (95% confidence); Launch 2020				
	Reduced emissions path	Discount rate		
Triggered on		2.50%	3%	5%
CLARREO	DICE Opt	59.083	31.920	3.623
	Lim 2.5 °C	103.409	50.892	2.514
	Stern	107.075	48.868	− 1.560
I/A/C	DICE Opt	49.188	25.987	2.635
	Lim 2.5C	88.002	42.559	1.965
	Stern	92.362	42.327	− 0.352
Difference in net benefits CLARREO Enhanced EOS − I/A/C				
	Reduced Emissions Path	Discount rate		
		2.50%	3%	5%
Surfeit net benefits	DICE Opt	9.894	5.933	**0.988**
	Lim 2.5 °C	**15.408**	**8.333**	0.549
	Stern	14.713	6.541	− 1.208

Red Em stands for Reduced emissions path.

of these results to temperature trigger magnitude and trigger confidence level finding the results robust to such changes. They also investigated the effect of delaying the launch of the improved climate observing system. A delay of 10 years reduced the VOI by 27% for the nominal DICE Optimal 3% discount scenario. The lost VOI per year of delay (US$ 250 billion) is about 30 times larger than the cost of increasing current global investments in climate observations by a factor of 3 (Cooke et al., 2013).

These considerations remind us that better information is only valuable if we use it in an intelligent way, leading into real option theory which is discussed next.

7. Real option value of EOS

When an EOS is placed in a decision context, where we have an array of choices to be exercised (or not) after deploying the EOS, we can express the value of the EOS as a real option value. In this section the choice of emissions scenario is not hard wired, but is made at the time the trigger is pulled, based on the state of knowledge after triggering and the discount rate. We are considering two such real options, one based on the existing EOS, and one based on the enhanced CLARREO EOS.

The real option value of the enhanced CLARREO EOS over and above the existing EOS is the surfeit expected net benefits of the 'right' to choose an emissions path triggered on CLARREO versus expected net benefits triggered on the existing system. As we show presently, for the same (unknown) value of *CS*, the time at which we pull the trigger and the emissions path which we then choose will differ for these two options. Hence, comparing net benefits conditional on the year in which we choose or on the emissions policy we select would not be correct. Real option theory provides the correct framework for this comparison.

Using the DICE functional relation between *CS* and temperature rise under BAU emissions, Figure 3 shows the date at which we would pull the trigger in the base case for the new CLARREO EOS, the current I/A/C EOS, and for a perfect EOS that is only limited by natural variability. For any value of *CS* the CLARREO EOS pulls the trigger earlier than the existing EOS, and almost reaches the perfect observing system values.

When an EOS triggers at a given year, our state of knowledge upon triggering can be read from the data used to produce Figure 3. If the trigger is pulled in 2040 with CLARREO, then we know that *CS* is greater than 3.404 and less than 4.732 (see left pair of dotted lines in Figure 3). Were *CS* lower than 3.404, the trigger would be pulled after 2040, were *CS* greater than 4.732 the trigger would have been pulled before 2040. Triggering in 2040 with the I/A/C system would occur if $8.537 \leq CS < 10$. For those values of *CS*, CLARREO would trigger in 2035. For $CS < 1.994$ neither EOS would trigger within the time frame of this analysis. Depending on our knowledge state, and our discount rate, we choose an emissions policy maximizing expected net benefits, from that time forward. For a given trigger year, the knowledge states induced by the two EOSs will differ, and for the same knowledge state, the trigger years will differ. For any knowledge state corresponding to a trigger, this state is induced earlier with CLARREO than with the existing EOS. If *CS* is such that the initial BAU emissions path is suboptimal, then under the existing EOS we remain longer on the suboptimal path than under CLARREO. This encapsulates the real option value of CLARREO relative to I/A/C.

The problem of optimizing expected net benefits over all emissions paths, though not infeasible, is nonetheless challenging. We should have to solve this problem for each EOS and for each trigger year. As noted, for this analysis, we restrict our choice to one of the emissions paths in Table 1. Figure 4 shows the surfeit expected net benefits of CLARREO versus I/A/C of the three reduced emission policies as functions of *CS*, for each of the three discount rates separately. The sharp step changes are an artifact

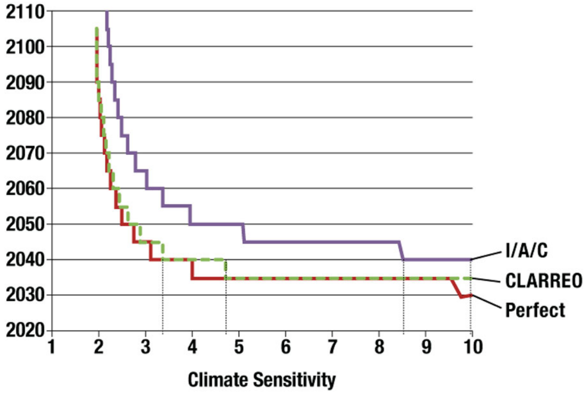

FIGURE 3 Trigger times for I/A/C, CLARREO and a perfect EOS under the base case, with trigger value 0.2 °C per decade, 2020 launch and $\sigma = 1.65$ (95% confidence).

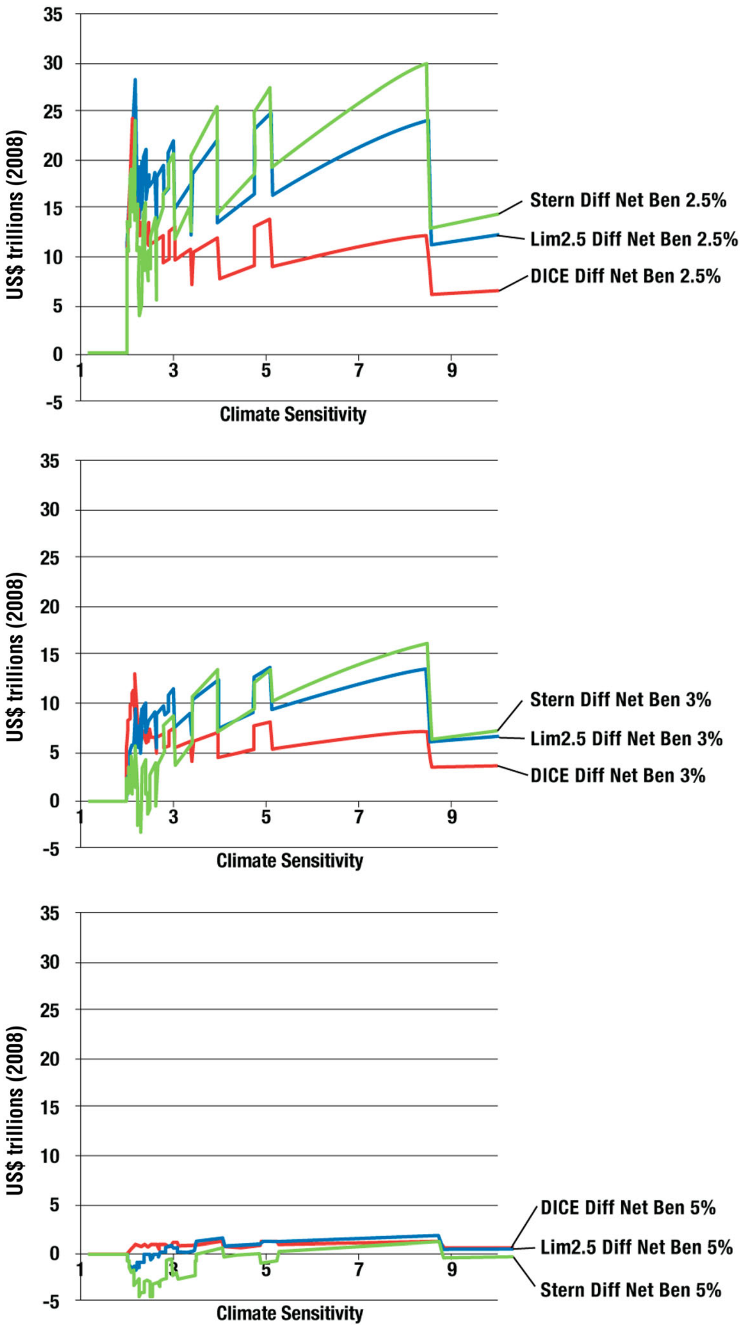

FIGURE 4 Surfeit net benefits for CLARREO versus I/A/C as functions of *CS*. The horizontal axis is (unknown) climate sensitivity, the vertical axis is surfeit benefits as a function of climate sensitivity. Jumps are caused by the 10 year discretization.

of the 5-year time discretization; a small difference in *CS* can shift the trigger date 5 years forward or backward. The higher the value of *CS*, the greater is the value placed on learning this information as early as possible, as reflected in the increasing step changes as *CS* increases.

There are a number of noteworthy features. First, at 5% discount rate, the surfeit expected net benefits when switching to the Stern emissions path are mostly negative, consistent with the facts noted above. For the other discount rates, the surfeit net benefits of switching to the DICE optimal or the Lim 2.5 °C paths are similar up to about $CS = 2.5$. For higher *CS* values, Lim 2.5°C exceeds DICE Optimal, with the Stern coming out on top for $CS > 3.5$ (2.5% discount rate) or 5 (3% discount rate). The benefit–cost ratio always favours the DICE Optimal path, as shown in Table 5, pointing out the well-known difference between net benefits and benefit–cost ratios.

These features highlight the importance of the real option value. There is a gain in expected net benefits if we can choose our reduced emissions path after observing the trigger value.

For this reduced problem, constraining the emissions path choice to one of the four defined here, and restricting to the base case, the real option value of the CLARREO EOS replacing the existing system I/A/C is shown in Table 6. The overall surfeit expected net benefits are US$ 16.7, 9 and 1.07 trillion (2008) for discount rates 2.5%, 3% and 5% respectively. These values are larger, though not dramatically larger, than the maximum values highlighted in bold in Table 4. That is, we could have done almost as well by choosing a reduced emissions path based solely on the discount rate. This is largely caused by the fact that the Stern path is strongly optimal for the two discount rates 2.5% and 3% only for $CS > 6$, which is an event with probability 10%. However, if we find ourselves in that situation we should not be content with the Lim 2.5 °C path. Indeed, there is no extra cost in deferring the choice of reduced emissions path until after the trigger is pulled. If we allow for a greater number of reduced emissions paths, our ability to optimize the choice of reduced emissions path after observing is greater and the differences between choosing before observing and choosing after observing would presumably become larger. The most ambitious approach encompassing a full stochastic optimization based on Bayesian updating of *CS* uncertainty promises larger real option value whose magnitude remains to be determined.

TABLE 5 Benefit–cost ratios for reduced emissions paths; Trigger = 0.2 °C per decade, sigma = 1.65 (95% confidence), launch 2020.

Benefit cost ratio: E(BAU(Damages) − Red Em(Damages) / Red Em(costs))

Triggered on	Reduced Emissions Path	Discount rate 2.5%	 3%	 5%
CLARREO	DICE Opt	6.341	5.815	3.791
	Lim 2.5C	2.303	1.942	1.057
	Stern	1.597	1.275	0.579
I/A/C	DICE Opt	5.648	5.186	3.450
	Lim 2.5C	2.116	1.785	0.974
	Stern	1.793	1.463	0.720

TABLE 6 Real option value of CLARREO broken down by discount rate (Trigger 0.2 ^{0}C per decade, sigma 1.65 (95% confidence), launch 2020).

Real option value of CLARREO enhanced EOS in trillions 2008 USD			
Discount rate	2.50%	3%	5%
Real option value	16.70	9.00	1.07

Intuitively, the meaning of the numbers in Table 6 is as follows: If the trigger is pulled early, then *CS* must be high, and in this case the best policy is a drastic reduction of emissions as in the Stern policy. At intermediate trigger values the Lim 2.5 °C policy yields the largest expected surfeit net benefits, and at late trigger values, *CS* is small and DICE Optimal is the best choice. This can reverse the conventional wisdom that the optimal climate policy involves modest reductions now and larger reductions later. The present analysis makes clear that the conventional wisdom holds only for low to modest values of *CS*. If *CS* is high and we have enabled an EOS to detect this fact early, then there is great advantage in switching to aggressive emissions reduction early. What constitutes ‘early’, ‘intermediate’ and ‘late’ is largely determined by the rate at which future losses are discounted.

Table 6 summarizes option value as a sum of expected surfeit net benefits in base case, broken down by discount rate. The calculation is as follows:

1. 924 samples of *CS* are drawn from the truncated Roe Baker distribution for *CS*; for each value of *CS*, compute $NB_C(p, CS)$ and $NB_I(p, CS)$ as the net benefits if switching to emissions path p were triggered by CLARREO or by I/A/C. $\Delta NB(p,cs) = (NB_C(p,cs) - NB_I(p,cs))$; the value of ΔNB is determined by the difference in years at which CLARREO and I/A/C trigger. If CLARREO or I/A/C does not trigger for *CS*, then their respective NB values are zero.
2. For each *CS*, compute $\Delta NB(p, Cy(CS)) =$ average $\Delta NB(p,CS)$ over values of *CS* for which CLARREO triggers in the same year as *CS*, which year is denoted $Cy(CS)$.
3. For each $Cy(CS)$ compute $\Delta NB(Cy(cs)) = \mathrm{MAX}_{p\,=\,DICE,\ Lim\ 2.5,\ Stern}\ \Delta NB(p,Cy(cs))$. In other words, for any year in which CLARREO triggers, we first average the surfeit net benefits for each emissions path, then take the maximum of these averages over the emissions paths. By Jensen’s inequality, ‘Max Ave ≤ Ave Max’. This inequality represents what could be gained by introducing a one year time step instead of a 5-year time step.
4. Compute the Rreal option value (ROV) of CLARREO by summing over all trigger years $Cy(CS)$ of $\Delta NB(Cy(cs)) \times Cy(cs)| / 924$, where $|Cy(CS)|$ is the number of values of *CS* which trigger in year $Cy(CS)$ with CLARREO.

Depending on discount rate a real option value of the CLARREO-enhanced EOS could be estimated in an interval from US $1 trillion to 16 trillion (2008). If we had used a one year time step, as intimated in step (3) of the algorithm sketched above, the ROVs would be 16.74, 9.04 and 1.08 for discount rates 2.5%, 3% and 5% respectively. Additional gains could be attained by increasing the set of reduced emission paths over which we optimize in step (3).

8. Conclusions

Uncertainty of the climatic system is one of the most important reasons for politicians to delay adoption of a comprehensive climate policy. This article demonstrates that deployment of a higher-accuracy Earth observation system could significantly reduce uncertainty to the level acceptable for decision making on long-term climate policy in a timely manner to prevent catastrophic events and to avoid prohibitive high costs of an urgent and drastic GHG reduction. The learning process, as described in this article, can take from 10 to 40 years. This time period is shorter for higher climate sensitivities.

It may be noted that a real option value in the range of US$1 to 20 trillion is small relative to the world economy. Indeed, DICE projects a world capital in 2100 of US$ 2319 trillion (or about US$ 190 trillion in present value calculated with 3% discount rate). Relative to the present value of abatement cost calculated with 3% discount rate for the DICE optimal scenario (about US$ 20 trillion) and for the Stern scenario (about US$ 100 trillion), the real option value of US$ 9 trillion is not insignificant.

More important in our view is the need to expand this type of accounting method to other potential measurements, thereby enabling society to better assess the relative benefits of competing economic investments. We currently lack an international climate observing system (Trenberth et al., 2013) due to its large perceived cost. Further studies of the economic value of climate observations such as cloud and carbon cycle feedbacks, aerosol forcing, sea-level rise, ocean acidification, ice sheet and glacier changes, and so on, would help to clarify the urgent need and high economic value.

Disclosure statement

No potential conflict of interest was reported by the authors.

Notes

1. An abatement cost in DICE 2009 has the same analytical representation as in DICE 2007 (Nordhaus, 2008) or in DICE 2013 (Nordhaus & Sztorc, 2013). The abatement cost is expressed in units of output and has the form of a convex function of the share of abated flow emissions. Exogenous technological changes (which reduce abatement cost) are captured in the scaling coefficient.
2. The "DICE optimal emissions path optimizes social welfare for climate sensitivity equal to 3 °C, for other values it is not optimal.
3. The underlying model is written in VBA and is relatively easy to use with the excel version of DICE 2009. Authors will send source code upon request.
4. The units in eq (1) are $(^{\circ}\mathrm{C}\ \mathrm{yr}^{-1})^2$.
5. Switching to the 2.5 °C stabilization path does not mean that temperature in 2100 is stabilized at 2.5 °C. When the policy is adopted upon the trigger being met, the emissions then are reduced to the level required in that year on the new emissions pathway. There is no make-up for the past ‘over accumulated’ emissions (the difference in total emissions between BAU and the new emissions pathway). There would be a ‘cliff’ effect with a radical drop in emissions at time of switch to the new pathway. Since emissions are not made up for to reflect the full reduction path of the original policy, then the policy path would no longer attain the original goal associated with it (e.g. you wouldn’t hit the 2.5 °C goal, or what DICE thinks is optimal). This aspect of the decision problem and calculation is beyond the scope of this article.

6. This is based on (Nordhaus, 2008), where Stern industrial emissions per decade are given out to 2105. Industrial emissions for Stern are zero beyond 2095. Total Stern emissions are determined by adding emissions due to land-use changes, which are the same for all scenarios.

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