A cost-effectiveness metric for climate mitigation policies

Christopher Monckton of Brenchley[1]

Abstract

A mitigation equation derived from climate-sensitivity estimates by the Intergovernmental Panel on Climate Change determines how much global warming any proposed reduction in CO2 concentration might forestall. The equation serves as the basis of a metric for determining and comparing the cost-effectiveness of policies intended to mitigate anthropogenic warming by taxing, regulating or reducing fossil-fuel consumption. Case studies indicate that mitigations unambitious enough to be affordable will be ineffective, while strategies radical enough to be effective will be unaffordable. Any mitigation is likely to prove cost-ineffective when set against the later and lesser costs of focused adaptation to global warming's consequences.

[1] Carie, Rannoch, PH17 2QJ

Introduction

How much anthropogenic warming will a given policy intended to mitigate it by reducing CO2 emissions forestall? The answer is a prerequisite for determining the cost-effectiveness of investment in mitigation of global warming: yet, remarkably, the question has received little attention to date. The present paper offers an equation that determines the quantum of anthropogenic warming likely to be forestalled by any proposed mitigation policy, as the basis for a simple metric allowing policy-makers to compare simply and directly the cost-effectiveness of mitigation policies.

The equilibrium warming equation and its derivation

The Intergovernmental Panel on Climate Change (IPCC: Solomon *et al.,* eds., 2007), estimates that, in response to a doubling of atmospheric CO2 concentration, equilibrium climate sensitivity ΔT_{equ} will be 3.26 ± 0.69 K to 1 s.d. (ch. 10, p. 798, box 10.2). However, the *Summary for Policymakers* (Solomon, p. 12) gives 3[2, 4.5] K, values outwith this interval being thought theoretically possible but unlikely. For simplicity, these two estimates are conflated in Eq. (1):

$$\Delta T_{equ} \approx 3.25 \pm 1.25 \text{ K.} \tag{1}$$

In the IPCC's methodology, ΔT_{equ} is the product of three parameters:

- **the radiative forcing $\Delta F = \alpha \ln(C/C_o)$** W m^{-2} (Myhre *et al.,* 1998), defined by Houghton *et al.,* eds. (2001: ch. 6.1) as the change in net radiative flux at the tropopause after stratospheric temperatures have readjusted to radiative equilibrium, with surface and tropospheric temperatures held unperturbed, where (C/C_o), the proportionate change in concentration, equals 2 at any CO2 doubling;
- **the Planck climate-sensitivity parameter $\kappa = 3.2^{-1}$** K W^{-1} m^2 (Solomon, Ch. 8., p. 631, fn.), which, multiplied by a forcing, gives consequent warming where temperature feedbacks (additional forcings triggered by the temperature change wrought by the original forcing) are net-zero;
- **the unitless temperature-feedback factor $f = (1 - b\kappa)^{-1}$** (Bode, 1945), which mutually amplifies the sum b in W m^{-2} K^{-1} of all positive (amplifying) and negative (attenuating) temperature feedbacks.

The product of κ and f, written λ, is the final climate-sensitivity parameter. Then –

$$\Delta T_{equ} = \Delta F \kappa f = \lambda \Delta F = \lambda \alpha \ln(C/C_o) = n \ln(C/C_o).$$

The warming coefficient n is now derived. At CO2 doubling, where $(C/C_o) = 2$,

$$\Delta T_{equ} = n \ln 2 \approx (3.25 \pm 1.25) \text{ K.}$$

Thus, $$n \approx (3.25 \pm 1.25) / \ln 2 \approx (4.7 \pm 1.8),$$

so that $$\Delta T_{equ} = n \ln(C/C_o) \quad | \quad 2.9 \le n \le 6.5 \tag{2}$$

The mitigation equation

The IPCC distinguishes between warming when the climate has returned to equilibrium after a perturbation such as Man's influence on CO2 concentrations, and the lesser, transient warming during some shorter period. The distinction is expressed in the final-climate-sensitivity parameter λ. From Eqs. (1-2), the equilibrium values implicit in Solomon are $\lambda_{equ} \approx 0.88[0.54, 1.21]$ K W^{-1} m^2.

Ramanathan *et al.* (1985) take 0.5 K W^{-1} m^2 as a typical value for λ, saying other values are possible. Solomon implicitly takes Ramanathan's value as the central estimate of λ for determining transient warming this century (the upper and lower bound are here derived from the central estimate): $\lambda_{tra} \approx 0.50[0.31, 0.69]$ K W^{-1} m^2. Then the IPCC's implicit transience ratio (i.e. the ratio of transient to equilibrium warming) for warming expected by the end of the 21st century is $r = \lambda_{tra} / \lambda_{equ} \approx 0.57$.

The transience ratio r generalizes Eq. (2) to yield the mitigation equation:

$$\Delta T_{nix} = r\, n \ln(C_y/C_{pol}), \quad | \quad r=1 \text{ at equilibrium, else } r<1 \quad | \quad 2.9 \le n \le 6.5 \tag{3}$$

such that y is the target calendar year by which it is intended that a given mitigation target shall have been attained, and C_y is the IPCC's projected business-as-usual CO2 concentration in year y. C_{pol}, the lesser concentration expected in year y as a result of the mitigation policy, is –

$$C_{pol} = C_y - p(C_y - C_{2010}), \tag{4}$$

where p is the fraction of future global emissions to be reduced by the target year y.

At eventual equilibrium, in this and all case studies, the warming forestalled would exceed the 21st-century transient warming by some 75%: however, equilibrium may be 1000 years away (see e.g. Solomon *et al.*, 2009), allowing plenty of time for gentle adjustment to the difference between transient warming to the IPCC's horizon of 2100 and eventual equilibrium warming. For this reason, though the transience ratio r in Eq. (3) allows determination of equilibrium as well as transient warming, it is the lesser, transient warming that is policy-relevant.

For policymakers' convenience, decadal values of C_y are given in Table 0, based on emissions scenario A2 in Solomon, which more closely replicates observed emissions than the other five scenarios and projects that the anthropogenic fraction of CO2 concentration will grow exponentially from 390 ppmv in 2010 to $C_{2100} \approx 836[730, 1020]$ ppmv in 2100.

Though CO2 *emissions* are rising at the high end of the IPCC's projections, for more than a decade CO2 *concentrations* have been rising not at the exponential rate projected by the IPCC on its A2 emissions scenario but at a near-linear 2 ppmv yr^{-1}. Values in row 4 of Table 0 assume this linear rate of will continue so that, in any year y from 2010-2100, $C_y = 390 + 2(y - 2010)$, reaching 570 ppmv by 2100.

y	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
Max.	390	416	448	488	537	597	672	764	879	1020
Cent.	**390**	**412**	**438**	**469**	**506**	**551**	**604**	**668**	**744**	**836**
Min.	390	409	430	456	486	521	561	609	665	730
+2/yr	390	410	430	450	470	490	510	530	550	570

Table 0. Projected CO2 concentrations C_y (ppmv) for the years $2010 \le y \le 2100$, in decadal increments, if CO2 concentration C_y rises exponentially from 390 ppmv in 2010 to $C_{2100} \approx 1020$, 836, or 730 ppmv respectively by 2100 (rows 1-3), or rises linearly at 2 ppmv yr^{-1} year from 390 ppmv in 2010 to 570 ppmv over the same 90-year period (row 4).

Intra-decadal values of C_y may be determined using Eq. (5). Atmospheric CO_2 concentration stands at 390 ppmv compared with 280 ppmv in 1750, so that the anthropogenic component is currently 110 ppmv. It is assumed that all increases in CO_2 concentration since 1750 are anthropogenic. On this basis, in any calendar year y in the 90 years 2010-2100, projected CO_2 concentration C_y on the A2 scenario is

$$C_y \approx 280 + 110\,e^q \quad | \quad q = [(y - 2010)/90] \ln[(C_{2100} - 280)/110] \qquad (5)$$

The cost-effectiveness metric

Once the mitigation equation has found ΔT_{nix}, the quantum of warming forestalled, and once the financial cost f of implementing a proposed mitigation strategy has been determined, the policy's cost-effectiveness metric M, denominated in US$ per Kelvin forestalled, is simply $f / \Delta T_{\text{nix}}$ (Eq. 6). The greater the value of M, the less cost-effective the policy, allowing direct comparison of competing mitigation strategies.

Policymakers wishing to obtain directly a rapid and reasonable central estimate of the cost-effectiveness of a proposed mitigation strategy intended to take effect this century may take n = 4.7 from Eq. (2), r = 0.57 (so that $n\,r \approx 2.67$), and CO_2 concentration 390 ppmv from the NOAA's data (Keeling *et al.,* 1976; Thoning *et al.,* 1989), yielding the cost-effectiveness metric in Eq. (6):

$$M = \frac{f}{\Delta T_{\text{nix}}} = \frac{f}{2.67 \ln[C_y/\{C_y - p(C_y - 390)\}]}. \qquad (6)$$

Thus, the cost-effectiveness of a proposed mitigation strategy becomes a function of just two case-specific parameters: the cost f, and the proportion p of future global anthropogenic emissions that the strategy is expected to forestall by the target year y.

A few case studies will demonstrate the applicability of the cost-effectiveness metric (Eq. 6) in evaluating and comparing policy options. In each case study, five values n = 2.9, 3.7, 4.7, 5.7, 6.5 of the coefficient in Eq. (2) will be applied, to encompass the wide interval of climate-sensitivity estimates in Solomon.

Case study 1: **Full implementation of the US cap-and-trade Bill**

The US emits 20% of global CO_2. The objective of the cap-and-trade Bill standing in the name of Congressmen Henry Waxman and Ed Markey is to phase out 83% of US CO_2 emissions by 2050. The policy, if phased in over the 40-year period, would thus reduce global emissions by half of 83% of 20%, or 8.3%. Thus p = 0.083 and, by Eq. (4), C_{pol} = 525 ppmv, so that a high-end estimate of warming forestalled is ΔT_{nix} = 0.084 K.

The US Government estimates that cost of forestalling this warming via the cap-and-trade Bill is $180 bn/year for 40 years – a total of $7.2 trillion. Thus, on the assumption that the US Government has correctly estimated the cost of implementing the Waxman/Markey Bill, the cost-effectiveness metric M is $86 trillion per Kelvin of warming forestalled. This is disproportionately costly, at 6 years' global GDP (or 6% of GDP over a century). Table 1 shows the global warming forestalled if the Bill were fully implemented.

Scenario:	C_{2100}	C_y	C_{pol}	n = 2.9	n = 3.7	n = 4.7	n = 5.7	n = 6.5
A2 max.:	1020	537	**524**	0.038 K	0.048 K	0.061 K	0.075 K	0.085 K
$M = f / \Delta T_{nix}$				***$190tr***	***$149tr***	***$117tr***	***$97tr***	***$85tr***
A2 centl.:	836	506	**496**	0.032 K	0.041 K	**0.051 K**	0.062 K	0.071 K
$M = f / \Delta T_{nix}$				***$227tr***	***$178tr***	***$140tr***	***$115tr***	***$101tr***
A2 min.:	730	486	**478**	0.027 K	0.035 K	0.044 K	0.054 K	0.061 K
$M = f / \Delta T_{nix}$				***$264tr***	***$207tr***	***$163tr***	***$134tr***	***$118tr***
2 ppmv yr^{-1}:	570	470	**463**	0.024 K	0.030 K	0.038 K	0.046 K	0.053 K
$M = f / \Delta T_{nix}$				***$306tr***	***$240tr***	***$189tr***	***$156tr***	***$137tr***

Table 1. Mitigation cost-effectiveness of the Waxman-Markey cap-and-trade Bill in the US, cutting global emissions stepwise by an average of 8.3% over the 40 years 2010-2050. The table shows projected CO2 concentrations C_{2100} on IPCC scenario A2, C_y in the policy's target year of 2050 if business continues as usual; C_{pol} in 2050 if the US Government's policy is implemented; and a range of estimates of the global warming the policy may forestall. The central estimate is highlighted. Cost-effectiveness M, in $tr/K forestalled, is in ***bold italics.***

Case study 2: **Closure of 80% of the United Kingdom's carbon economy**

The stated aim of the Climate Change Act is that 80% of the UK's carbon economy will be closed down by y = 2050, the target year for the calculation. The UK accounts for 2% of global CO2 emissions.Without the policy change, if CO2 concentration were to increase exponentially at the centre of the A2 scenario's projections, by 2050 CO2 concentration C_y would be 506 ppmv (table 0, row 2). However, if the UK were to reduce CO2 emissions stepwise over 40 years, future global emissions would be reduced by half of 80% of 2%, or 0.8%, so that p = 0.008. Then, from Eq.. (4), in 2050 C_{pol} would be 505 ppmv.

Taking the central estimate n = 4.7 of the warming coefficient n in Eq. (2), ΔT_{nix}, a central estimate of the transient global warming forestalled by a phased-in 80% cut in the UK's carbon emissions from 2010 to 2050, 4.7 x 0.57 ln(506/505), or 0.005 K.

The UK's Climate Change Act is officially projected to cost US $30 billion (£18 bn sterling) annually for 40 years: total cost f = $1.2 trillion. If the UK Government's costing of its climate strategy is correct, cost-effectiveness M is $1.2 tr / 0.005K, or $244 tr/K forestalled. At that rate, forestalling the 3.4 K transient global warming that the IPCC (on scenario A2) expects by 2100 would consume 11 years' total world GDP, currently some $75 trillion/year at purchasing-power parities.

Scenario:	C_{2100}	C_y	C_{pol}	n = 2.9	n = 3.7	n = 4.7	n = 5.7	n = 6.5
A2 max.:	1020	537	**535**	0.004 K	0.005 K	0.006 K	0.007 K	0.008 K
$M = f / \Delta T_{nix}$:				***$332tr***	***$260tr***	***$205tr***	***$169tr***	***$148tr***
A2 centl.:	836	506	**505**	0.003 K	0.004 K	**0.005 K**	0.006 K	0.007 K
$M = f / \Delta T_{nix}$				***$395tr***	***$310tr***	***$244tr***	***$201tr***	***$176tr***
A2 min.:	730	486	**485**	0.003 K	0.003 K	0.004 K	0.005 K	0.006 K
$M = f / \Delta T_{nix}$				***$460tr***	***$361tr***	***$284tr***	***$234tr***	***$205tr***
2 ppmv yr^{-1}:	570	470	**469**	0.002 K	0.003 K	0.004 K	0.004 K	0.005 K
$M = f / \Delta T_{nix}$				***$533tr***	***$418tr***	***$329tr***	***$271tr***	***$238tr***

Table 2. Warming forestalled by eliminating 80% of UK emissions stepwise by 2050, reducing global emissions by a mean 0.8%.

Case study 3: **The Thanet Wind Array**

The largest offshore wind-farm on Earth is the Thanet wind array off the Kent coast in England. The State subsidy to this array, guaranteed at £60 million annually for its 20-year lifetime, is $2 billion. The rated output of the 100 turbines, which each cost $13 million to build, is 300 MWh: however, in practice, wind-farms deliver only 26% of rated capacity. Accordingly, the total likely output of the Thanet wind array, at 78 MW, is a little under 0.2% of total UK electricity demand, which is ~40 GWh. Electricity represents ~40% of total UK CO2 emissions, which in turn represent 2% of global emissions. Accordingly, p = 0.0000156. Table 3 demonstrates the mitigation cost-effectiveness of the Thanet wind array. The highlighted central estimate implies that mitigating the 3.4 K global warming predicted by the IPCC for the 21st century would consume 20% of global GDP.

Scenario:	C_{2100}	C_y	C_{pol}	n = 2.9	n = 3.7	n = 4.7	n = 5.7	n = 6.5
A2 max.:	1020	448	**448**	0.000 K	0. 000 K	0. 000 K	0. 000 K	0. 000 K
$M = f / \Delta T_{nix}$				***$599tr***	***$558tr***	***$439tr***	***$362tr***	***$318tr***
A2 centl.:	836	438	**438**	0.000 K	0. 000 K	**0. 000 K**	0. 000 K	0. 000 K
$M = f / \Delta T_{nix}$				***$712tr***	***$558tr***	***$439tr***	***$362tr***	***$318tr***
A2 min.:	730	430	**430**	0.000 K	0. 000 K	0. 000 K	0. 000 K	0. 000 K
$M = f / \Delta T_{nix}$				***$826tr***	***$647tr***	***$509tr***	***$420tr***	***$368tr***
2 ppmv yr⁻¹:	570	430	**430**	0.000 K	0. 000 K	0. 000 K	0. 000 K	0. 000 K
$M = f / \Delta T_{nix}$				***$834tr***	***$653tr***	***$514tr***	***$424tr***	***$372tr***

Table 3 Mitigation cost-effectiveness of the Thanet wind array.

Case study 4: **The Mayor of London's bicycle-hire scheme**

In 2010 the Mayor of London established a scheme State bicycle-hire scheme at a cost of US$130 million (£82 million sterling) for 5000 bicycles, or more than $26,000 per bicycle. Assuming that transport accounts for 25% of UK emissions, that cycling accounts for 10 billion of the 800 billion vehicle miles traveled on UK roads in a year, and that 5 million new cycles join the UK's roads each year, global emissions will be reduced by 2% of 25% of 10/800 times 5000/5,000,000, so that p = 6.25 x 10^{-8}. It will be assumed that the lifetime of the bicycles, docking stations and ancillary equipment is 20 years. Table 4 shows the mitigation cost-effectiveness of the policy, which the Mayor of London described as a "Rolls-Royce scheme". To forestall 3.4 K global warming this century on the basis of schemes such as this, 100% of global GDP would be consumed for approximately a third of a millennium.

Scenario:	C_{2100}	C_y	C_{pol}	n = 2.9	n = 3.7	n = 4.7	n = 5.7	n = 6.5
A2 max.:	1020	448	**448**	0.000 K	0. 000 K	0. 000 K	0. 000 K	0. 000 K
$M = f / \Delta T_{nix}$				***$9.7qd***	***$7.6qd***	***$6.0qd***	***$4.9qd***	***$4.3qd***
A2 centl.:	836	438	**438**	0.000 K	0. 000 K	**0. 000 K**	0. 000 K	0. 000 K
$M = f / \Delta T_{nix}$				***$11.5qd***	***$9.1qd***	***$7.11qd***	***$5.9qd***	***$5.2qd***
A2 min.:	730	430	**430**	0.000 K	0. 000 K	0. 000 K	0. 000 K	0. 000 K
$M = f / \Delta T_{nix}$				***$13.4qd***	***$10.5qd***	***$8.3qd***	***$6.8qd***	***$6.0qd***
2 ppmv yr⁻¹:	570	430	**430**	0.000 K	0. 000 K	0. 000 K	0. 000 K	0. 000 K
$M = f / \Delta T_{nix}$				***$13.5qd***	***$10.6qd***	***$8.3qd***	***$6.9qd***	***$6.0qd***

Table 4. Mitigation cost-effectiveness of the Mayor of London's $130m bicycle-hire scheme, in quadrillions of US dollars per Kelvin of warming forestalled.

Results

Table 5 summarizes the mitigation cost-effectiveness and global GDP costs of the mitigation strategies in the four illustrative case studies. For comparison, the table also includes the estimates in Stern (2006) that climate change can be mitigated at a cost of 1% of global GDP, and that climate-related damage in the absence of mitigation would cost 5-20% of global GDP.

Mitigation Strategy	Mitigation cost-effectiveness *M*	% global GDP
$2 bn subsidy to a 1GW nuclear plant	**$17** trillion per Kelvin	**0.8%** GDP
Stern: achievable global mitigation cost	**$22** trillion per Kelvin	**1%** GDP
Stern: minimum climate-change damage	**$110** trillion per Kelvin	**5%** GDP
1: US Climate Change Bill	**$140** trillion per Kelvin	**6%** GDP
2: UK Climate Change Act	**$244** trillion per Kelvin	**11%** GDP
3: Thanet wind array	**$439** trillion per Kelvin	**20%** GDP
Stern: maximum climate-change damage	**$441** trillion per Kelvin	**20%** GDP
4: London bicycle-hire scheme	**$7128** trillion per Kelvin	323% GDP

Table 5. Mitigation cost-effectiveness *M* and global GDP cost of mitigating the 3.4 K transient global warming that the IPCC projects for the 21st century, on case-studies 1-4, compared with the 1%-GDP mitigation cost suggested as achievable by Stern (2006), and with Stern's estimated 5-20%-GDP cost of climate-change-induced damage if no mitigation is undertaken.

Discussion

The cost-effectiveness metric for climate mitigation policies that is described and justified here is intended to offer a necessary and accessible quantitative starting-point for determining the global warming that would be forestalled by any given mitigation strategy and the consequent mitigation cost-effectiveness of that strategy.

The four case studies demonstrate that regional-scale mitigation, such as shutting down 80% of the UK's carbon economy over the next 40 years, would forestall very little global warming. Even if a similar fraction of the US carbon economy were closed down stepwise to 2050, the global warming forestalled would be negligible and the cost disproportionate.

If the US and UK Governments have understated the costs of achieving the very large reductions in CO2 emissions that they plan, then the cost-ineffectiveness of their policies will prove even worse than it is when based on their own cost estimates. The UK Department of Energy and Climate Change, consulted during the preparation of this paper, confessed that it had not carried out any mitigation cost-effectiveness calculations at all when formulating its climate strategy, now enacted in law.

One indication that the official government figures for the cost of mitigation may be substantial underestimates is that the mitigation projects in case studies 3-4 are significantly less cost-effective than the US and UK governments' figures for overall mitigation policy in case studies 1-2. The cost-effectiveness of individual projects is based on their known costs, while that of long-term government strategies is based not on the sum of individual projects at known cost but on estimates which appear optimistic and may be uncosted.

Though the London Mayor's cycle-hire scheme is economically unjustifiable and is more likely to be taken as a warning against *grands projets* than as a precedent, the Thanet Wind Array is planned as the first of many. Onshore wind-farms are no longer acceptable to their neighbors, and their environmental cost is now widely known. However, as the remarkable cost-ineffectiveness of the Thanet array demonstrates, the heavy costs of construction and maintenance render offshore wind-farms even more cost-ineffective than those onshore.

The UK Government could have spent the $2 billion Thanet subsidy on subsidizing a zero-carbon-emitting nuclear power station, which would have generated 13 times as much electricity for twice the Thanet wind-farm's 20-year lifetime, and would have repaid the subsidy well before the end of the 40 years. Even without repayment, the mitigation cost-effectiveness of the $2 billion subsidy to a nuclear power station would be 26 times more cost-effective than the Thanet array – equivalent to $17 trillion per Kelvin of global warming forestalled, and close to the global mitigation cost that Stern holds to be achievable. As it is, the GDP cost-effectiveness measure as applied the British Government's climate strategy – attributable in no small part to its concentration on wind-farms – is an order of magnitude greater than Stern's 1% of GDP.

Only with drastically large-scale global mitigation over a long period would an appreciable quantum of long-run global warming be forestalled. At present, the only large-scale zero-carbon method of electricity generation that is available, affordable, and to some extent cost-effective is nuclear power.

Herein lies one of the two central economic problems posed by any attempted mitigation of future anthropogenic global warming by reducing CO_2 emissions. Any reduction small enough to be affordable will have no measurable effect on the climate, while any reduction large enough to have a measurable effect on the climate will be unaffordable.

The second problem is that, as these results strongly suggest, any attempt at mitigation would probably be orders of magnitude less cost-effective than focused adaptation to any anthropogenic global warming that may occur, where and if it occurs. Policymakers might in normal circumstances consider abandoning the mitigation pathway altogether. However, the IPCC was structured from the outset in such a way that mitigation and adaptation were considered in separate working groups. For this and other reasons, the relative costs and benefits of mitigation and adaptation have not been directly compared in the literature to date.

Also, because a cost-effectiveness metric such as that which is outlined here has not been available, the relative costs and benefits of individual mitigation strategies have not been directly compared. Accordingly, wind-farms, solar panels and other policies have been implemented not because they are cost-effective but because they are fashionable.

It is possible that the true cost-ineffectiveness of measures intended to mitigate global warming by reducing carbon dioxide emissions will be considerably worse than the case studies suggest. If, for instance, climate sensitivity turns out to be at the lower end of the IPCC's projections, and if the atmospheric residence time of CO_2 is as great as the IPCC considers it to be, then, for instance, the cost per Kelvin of global warming forestalled in the examples above will be more than double the already high values shown.

It has been demonstrated theoretically (*e.g.* Lindzen, 2007; Schwartz, 2007; 2010; Monckton of Brenchley, 2008) and confirmed empirically by direct measurement of outgoing radiation from the Earth's characteristic-emission level (*e.g.* Lindzen and Choi, 2009 (but see Fassullo *et al.,* 2009); Covey, 1995; Chen *et al.,* 2002; Cess & Udelhofen, 2003; Hatzidimitriou *et al.* 2004; Clement & Soden, 2005) and by direct measurement of ocean temperatures in the mixed layer (Lyman *et al.,* 2006 as amended, Gouretski & Koltermann, 2007, Willis, 2008, and Loehle, 2009, all show ocean cooling; Willis *et al.*, 2009, show no ocean warming; Douglass & Knox, 2010, show no net accumulation of heat-energy in the mixed layer over the past five years); that the IPCC's current central estimate of climate sensitivity to atmospheric CO_2 enrichment may be substantially exaggerated. If so, a corresponding reduction in the coefficient n in Eqs. (2-3) and consequently in the quantum of warming forestalled and in the cost per Kelvin of warming forestalled is mandated.

Note also that in this metric it is optimistically assumed that the effects of any policy changes on temperature will be immediate, notwithstanding the contention in Solomon *et al.* (2007), that the atmospheric residence-time of CO_2 is 50-200 years.

Conclusion

This paper has attempted to take the complexities of the IPCC's analysis and simplify them – but without loss of accuracy – to the point where policymakers unfamiliar with climate science will be able to use the metric described here as a starting-point for evaluating the relative cost-effectiveness of competing mitigation strategies.

As the case studies demonstrate, the cost-effectiveness of most attempts to mitigate CO_2 emissions, measured in trillions of dollars per Kelvin of anthropogenic global warming forestalled, is so heavy that it may be expected extravagantly to outweigh any climatic benefits. Some mitigation strategies may even outweigh the cost of climate-related damage if the do-nothing option is followed.

Since the cost of mitigation is so high, and since global warming <2 K is generally regarded as harmless, the cost of mitigation may well prove to be orders of magnitude greater than that of focused adaptation to the consequences of any future climate change that may occur. If so, the question arises whether most mitigation policies should be pursued at all.

References

CESS, R.D., and P.M. Udelhofen. **2003.** Climate change during 1985–1999: Cloud interactions determined from satellite measurements. *Geophysical Researh Letters* **30,** 1: 1019, doi:10.1029/2002GL016128.

CHEN, J., B.E. Carlson, and A.D. Del Genio. **2002.** Evidence for strengthening of the tropical general circulation in the 1990s. *Science* **295:** 838-841.

CLEMENT, A.C., and B. Soden. **2005.** The sensitivity of the tropical-mean radiation budget. *J. Clim.* **18:** 3189-3203.

COVEY, C. 1995. Correlation between outgoing long-wave radiation and surface temperature in the tropical Pacific: a model interpretation. Lawrence Livermore National Laboratory, Livermore, CA 94551, November. UCRL-ID-122565.

GOURETSKI, V., & K.P. Koltermann. **2007.** How much is the ocean really warming? *Geophysical Research Letters* **34**: 10.1029/2006GL027834.

HATZIDIMITRIOU, D., I. Vardavas, K. G. Pavlakis, N. Hatzianastassiou, C. Matsoukas, and E. Drakakis. **2004.** On the decadal increase in the tropical mean outgoing longwave radiation for the period 1984–2000. *Atmos. Chem. Phys.* **4:** 1419–1425.

HOUGHTON, J.T., Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell & C.A. Johnson (eds.). **2001.** *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, and New York, USA.

KEELING, C.D., R.B. Bacastow, A.E. Bainbridge, C.A. Ekdahl, P.R. Guenther, and L.S. Waterman. **1976.** Atmospheric carbon dioxide variations at Mauna Loa Observatory, Hawaii. *Tellus* **28:** 538-551.

KNOX, R.S., and D. Douglass. **2010.** Recent energy balance of Earth. *Int. J. Geosci.* **1:3** [in press]: doi:10.4236/ijg2010.00000. Published online (http://www.scirp.org/journal/ijg).

LINDZEN, R.S. **2007.** Taking greenhouse warming seriously. *Energy & Environment* **18:** 7-8, 937-950.

LINDZEN, R.S., and Y-S. Choi. **2009.** On the determination of climate feedbacks from ERBE data. *Geophys. Res. Lett.*

LOEHLE, C. 2009. Cooling of the global ocean since 2003. *Energy & Environment* **20,** 1-2: 101-104. **DOI** 10.1260/095830509787689141.

LYMAN, J.M., J.K. Willis, and G.C. Johnson. **2006.** Recent cooling of the upper ocean. *Geophysical Research Letters* **33:** L18604, doi:10.1029/2006GL027033.

MONCKTON OF BRENCHLEY, C.W. **2008.** Climate sensitivity reconsidered. *Physics & Society* **37:** 3.

RAMANATHAN, V., R. Cicerone, H. Singh and J. Kiehl. **1985.** *Trace gas trends and their potential role in climate change.* J. Geophys. Res. **90:** 5547-5566.

SCHWARTZ, S.E. **2007.** Heat capacity, time constant, and sensitivity of Earth's climate system. *J. Geophys. R.*

SCHWARTZ, S. E., Robert J. Charlson, Ralph A. Kahn, John A. Ogren, Henning Rodhe. **2010.** Why Hasn't Earth Warmed as Much as Expected? *J. Clim.* **23**, 2453–2464; doi: 10.1175/2009JCLI3461.1

SOLOMON, S., Plattner, G-K., Knutti, R., and Friedlingstein, P. **2009.** *Irreversible climate change due to carbon dioxide emissions.* PNAS **106:6,** 1704-1709. DOI 10.1073 pnas. 0812721106.

SOLOMON, S., D. Qin, M. Manning, R.B. Alley, T. Berntsen *et al.* (eds.). **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, Cambridge, UK, and New York, USA.

STERN, N. **2006.** *The Stern Review: The Economics of Climate Change.* HM Treasury, London.

THONING, K.W., P.P. Tans, and W.D. Komhyr. **1989.** Atmospheric carbon dioxide at Mauna Loa Obervatory 2. Analysis of the NOAA GMCC data, 1974-1985, *J. Geophys. Res.* **94:** 8549-8565.

WILLIS, J. K. **2008.** Is it me, or did the oceans cool? *U.S. Cli. Var.* **6:** 2.

WILLIS, J.K., J.M. Lyman, G.C. Johnson and J. Gilson. **2009.** In-situ data biases and recent ocean heat content variability. *J. Atmos. & Oceanic Technology* **26:** 846-852.