BAU after 2010 in this scenario could only be achieved if decisions were made now with regard to future energy production, so this case certainly does not correspond to a 'no action' scenario.) Results for the 'High' case are shown in the bottom panels of Fig. 2 (concentration profiles based on non-Annex I departure dates of 2010, 2030 and 2050), Fig. 3 (implied global fossil CO_2 emissions) and Fig. 4 (implied emissions for non-Annex I countries).

For the 2010 departure date, the concentration profile is indistinguishable from WRE550, and the implied global emissions are virtually the same. This is not surprising, as the 'High' scenario assumes that emissions begin to decline below the IS92a 'no-intervention' case in 2010 for both groups of countries. This is the same as the assumption on which WRE550 was based, but here I specify the way global emissions reductions are apportioned between Annex I and non-Annex I countries. The departure dates of 2030 and 2050 correspond to different ways of apportioning the emissions restrictions: 2030 allows larger emissions for non-Annex I countries but requires a slightly earlier maximum and a slightly more rapid decline, whereas 2050 allows a much larger emissions maximum for non-Annex I countries but requires a very rapid decline.

In this analysis I have assumed that there is no coupling between emissions in Annex I and non-Annex I countries; such coupling could lead either to greater emissions in the latter group ('carbon leakage' through energy price or trade effects), or lower emissions (through technology diffusion or transfer). Coupling would also occur if there were trading of emissions rights between countries in the two groups. My results can easily be generalized to cover this possibility.

If A represents Annex I emissions, N represents non-Annex I emissions, and T is the emissions traded, then the present results may be considered as applying to 'effective' Annex I and non-Annex I emissions, defined by $A - T$ and $N + T$, respectively. The scenarios in Fig. 2 would then represent scenarios for $A - T$; actual Annex I emissions (A) would exceed these by the amount traded. Non-Annex I emissions would be less than the BAU values assumed here (by an amount T), taking advantage of economic efficiencies and/or technological advances that might diffuse from Annex I countries. The pathways shown here may then be considered as spanning a range of trading (or burden sharing) possibilities. Economic analyses could then be used to assess the relative costs of the different Annex I emissions-limitation cases, and, within these, the relative costs of different departure dates for non-Annex I emissions from BAU and of a range of assumptions with regard to the trading of emissions rights.

In summary, I have shown how the emissions-limitation burden to achieve CO_2 stabilization at 550 p.p.m.v. (roughly double the preindustrial level) might be shared between Annex I and non-Annex I countries. Choosing between different possibilities and between different stabilization levels requires careful analysis of their environmental and economic consequences. Reassuringly, even if Annex I emissions were to stay close to BAU until 2010 (as in the WRE550 case), this would not preclude stabilization. If, in this case, Annex I emissions were then to decline relative to BAU at the rates assumed here, this would allow emissions in non-Annex I countries to follow close to BAU until around 2030. More stringent (or earlier) Annex I restrictions would allow a later departure from BAU for non-Annex I countries. The result that significant departures below BAU emissions in non-Annex I countries could occur decades after those assumed for Annex I countries, when combined with the possibility of substantial wealth transfers through emissions trading from Annex I to non-Annex I countries, provides a foundation for a fair and equitable solution to the problem of climate change. □

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Influence of socioeconomic inertia and uncertainty on optimal CO_2-emission abatement

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Following the United Nations Framework Convention on Climate Change[1], governments will negotiate, in Kyoto this December, an agreement to mitigate anthropogenic greenhouse-gas emissions. Here we use a model approach to examine optimal CO_2-emission abatement paths for specified long-term constraints on atmospheric CO_2 concentrations. Our analysis highlights the interplay of uncertainty (in target greenhouse-gas concentrations) and the inertia in the energy systems that produce CO_2 emissions. We find that the 'integrated assessment' models previously applied to these issues under-represent inertia. A more appropriate representation of inertia increases the costs of deferring abatement and makes it optimal to spread the effort of abatement across generations. Balancing the costs of early action against the potentially higher costs of more rapid and forced later action, we show that early attention to the carbon-emitting potential of new and replacement energy investments will minimize the risk to environmental and economic systems. We conclude that if there is a significant probability of having to maintain atmospheric greenhouse gas concentrations below about double those of the pre-industrial era, then the economic risks associated with deferring abatement justify starting to limit CO_2 emissions from energy systems immediately.

Policy towards climate change faces uncertainty about the ultimate goal: we are not likely to know soon at what atmospheric concentration of greenhouse gases "dangerous interference with the climate system"[1] would occur. An initial emissions-abatement path consistent with reaching one selected concentration ceiling may have to be either accelerated or relaxed in the light of new scientific information. This is why the IPCC states that: " The choice of abatement paths involves balancing the economic risks of rapid abatement now (that premature capital stock retirement will later be proven unnecessary), against the corresponding risks of delay (that more rapid reduction will then be required, necessitating premature retirement of future capital")[2].

Incorporating such uncertainty into the analysis implies that the inertia of the economic systems producing greenhouse gases becomes critical. Energy production systems cannot be changed overnight and energy demand is driven by long-lasting patterns of infrastructure and behaviour. Without inertia, the transition costs for switching from one emission path to another would be null, and uncertainty would be less critical. But in a stochastic framework, inertia raises both the costs of premature abatement and the costs of accelerating abatement if stronger action is called for after a period of delay.

Here we analyse these issues using a compact intertemporal optimization model, DIAM, defined in Box 1. DIAM determines the least-cost CO_2-emission pathway consistent with staying below a given or stochastic atmospheric CO_2-emission pathway consistent with staying below a given or stochastic atmospheric CO_2 concentration ceiling, given assumptions concerning abatement costs; the rate r at which these costs are reduced by exogenous technical progress (that is, technical advance that is assumed to be independent of emissions abatement); the societal discount rate ρ (the annual rate of decline in the present value of costs and benefits incurred in the future); and the inertia in the system, D. We adopt parameters lying within the range of magnitude quoted in the literature for exogenous technical progress (1% per year) and for the societal discount rate (3% and 5% per year)[12], and for the model of carbon accumulation (Box 1). The inertia parameter, D, derived from the structure of abatement costs, is the novel aspect of the model and demands more discussion.

The abatement cost at time t is expressed as a quadratic function of both the degree and the rate of abatement (Box 1, equation 6). The nonlinearity of costs with respect to the degree of abatement x is well established[2]. By adding a term that depends upon the rate of abatement, A (akin to the time derivative of x), the model captures inertia explicitly. Modelling studies of capital stock turnover[3] confirm that costs depend in a nonlinear manner on the rate of abatement. In equation 6, additive separability between permanent costs (in $c_a(D)x^2$) and adjustment costs (in $c_a(D)D^2A^2$) makes it possible to explore the impact of transitional costs independently of long-run, permanent abatement costs[4]. For example, various transportation systems and urban planning patterns with very different carbon-emission potentials could have comparable operation costs. Innovations induced by carbon emissions constraints and cumulating over long periods could also reduce long-run costs to low levels. Nevertheless, starting one policy and then switching to another may entail high transition costs.

To test the sensitivity of our results with respect to the form of the cost function, we explore an alternative-specification equation 6a, in which adjustment costs are determined solely by comparing A with the rate of capital depreciation in the energy sector. As long as A is lower than the 'natural' pace of replacement of capital $1/D$, there are no adjustment costs and the reduction cost is proportional to x^2; above that pace, costs would be multiplied by max(1, DA).

Dimensional analysis in both specifications shows that D is a duration which can be interpreted as the characteristic timescale of changes in the global energy system. If interpreted purely in terms of capital depreciation at rate δ, then $D = (\ln 2)/\delta$.

This approach allows us to capture crucial dynamic constraints without resorting either to the arbitrary upper bound on emission reduction rates (as in refs 5, 6, 7) or to the limitations associated with representing inertia purely in terms of uniformly depreciating capital stock (as in ref. 3, 8, 9). DIAM gives approximately the same results as these latter models when we set $D = 20$ years (that is $\delta \approx 4\%$ per year), a reasonable average for the rate of renewal of appliances, cars, power stations or refineries, the lifetimes of which range from 10 to 40 years.

But there are many other sources of inertia in socioeconomic systems that produce greenhouse gases. Time is needed to remove market and institutional barriers to the diffusion of innovations, and obstacles arising from imperfect information and imperfect foresight. As has been demonstrated empirically[10], without specific policies, new energy sources have taken about 50 years to penetrate from 1% to only 50% of their ultimate potential. Furthermore, anthropogenic greenhouse-gas emissions depend in part on long-lived capital, such as buildings, transport and urban infrastructures with effects that may last more than 50 years, and on the linkages between different systems, such as the complex interlinked investments in mines, ports and power stations. Greenhouse-gas emissions today are still clearly influenced, perhaps strongly, by planning

Box 1 DIAM: a model of the dynamics of inertia and adaptability for integrated assessment of climate-change mitigation

Indices t, u refers to time periods; s refers to states of the world. DIAM[4] finds the optimal abatement strategy $x^*(s, t)$ by minimizing the total expected discounted abatement cost J, defined in equation (1) under constraints in equation (2), the concentration ceiling, and equation (3), dynamic programming. Equation (4) defines CO_2 atmospheric concentration $M(s, t)$, and equation (5) defines the acceleration of abatement $A(s, t)$. Abatement costs $C(s, t)$ are defined by equation (6). Alternatively, equation (6a) is used to test the sensitivity of the results to the shape of the cost function.

Time profile $E^{ref}(t)$ refers to anthropogenic fossil carbon emissions in IPCC scenario IS92a. The reference CO_2 concentration path $M^{ref}(t)$ is computed from IS92a total carbon emission with the atmospheric perturbation CO_2 response function $R(u)$ using a linear carbon cycle[6,12] (model W). $M^{ref}(1765)$, the CO_2 concentration before industrialization, was less than 280 p.p.m.v. The CO_2 concentration was 354 p.p.m.v. in 1990, increasing at 1.7 p.p.m.v. per year (ref. 6).

Reduction costs are determined by a social risk-free discount rate ρ (3% or 5%, to account for pending controversies); a technical progress rate r (1%), and a characteristic time of energy systems D (20 or 50 years). The costs scale $c_a(D)$ is normalized ($c_a(50) = 1.36$, $c_a(20) = 3.18$) so that total cost is similar to DICE's cost[4]. Note that when equation (6) is reported into equation (1), the $c_a(D)$ need no longer be under the integral, implying that the optimal $x^*(s, t)$ is independent of $c_a(D)$.

The stochastic concentration ceiling is defined by the number of alternatives examined, N; ceiling levels $L(s)$; subjective probabilities $p(s)$; and the date of uncertainty resolution t_{info}.

Results are shown in Table 1. First we examine certainty scenarios $N = 1$ for different values of D, ρ and L (sensitivity to r is mathematically the same as sensitivity to ρ). Then we explore $N = 3$ with equidistribution over {450, 550, 650} p.p.m.v., for $t_{info} = 2020$ and $t_{info} = 2035$.

$$J = \sum_{1 \le s \le N} p(s) \sum_{t=1997}^{t=2300} (1+\rho)^{t_0 - t} C(s,t) \qquad (1)$$

$$M(s,t) \le L(s) \qquad (2)$$

$$\forall t \le t_{info}, \forall s, 1 \le s \le N, x(s,t) = x(1,t) \qquad (3)$$

$$M(s,t) = M^{ref}(t) - 0.471 \sum_{u=t_0}^{u=t-1} R(t-u) x(s,u) E^{ref}(u) \qquad (4)$$

$$A(s,t) = x(s,t) - x(s,t-1) \qquad (5)$$

$$C(s,t) = c_a(D)(1+r)^{t_0 - t} \frac{E^{ref}(t)}{E^{ref}(t_0)} \left[x(s,t)^2 + D^2 A(s,t)^2\right] \qquad (6)$$

$$C(s,t) = c_a(D)(1+r)^{t_0 - t} \frac{E^{ref}(t)}{E^{ref}(t_0)} \left[x(s,t)^2 \max(1, DA(s,t))\right] \qquad (6a)$$

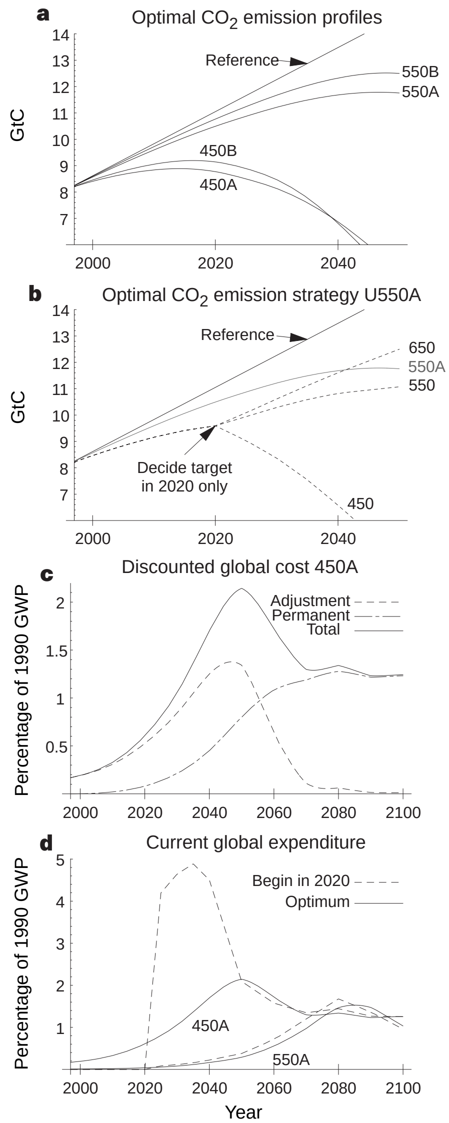

Figure 1 Optimal pathways under a given stabilization constant. The reference case, emissions increasing linearly by about 2% per year from the 1997 level, approximates the IPCC IS92a emissions scenario[14]. This is assumed to be least cost without constraints, so abatement shown is global average over and above any 'no regret' reductions. One GtC equals $[12 + (2 \times 16)]/12 = 3.67 \times 10^{12}$ kg of CO_2. **a**, Four optimal emission pathways that minimize the total abatement costs for the given concentration ceiling, inertia and discount rate (see Table 1). The B cases have lower inertia and higher discount rate than A, both factors leading to higher near-term optimal emissions. However, optimal policy is more sensitive to the ultimate concentration ceiling, 450 or 550 p.p.m.v. **b**, Optimal emission strategy U550A under stochastic constraint. The ultimate target is decided only in 2020, before which the strategy follows a precautionary path emitting less than the comparable case without uncertainty 550A. **c**, Cost as the sum of adjustment cost and permanent cost, optimal path 450A. The ratio:area under the 'Adjustment' curve discounted divided by area under the 'Total' curve discounted is the share of adjustment costs, labelled Adj./total in Table 1. **d**, Current expenditure profiles with (broken lines) and without (solid lines) a 20-years delay, for 450 and 550 p.p.m. stabilization targets (case A). For 450 p.p.m., cost peaks abruptly and is much higher with delay than without, owing to higher adjustment costs in the 2020–2040 period. Results are not that sharp for 550 p.p.m., as the time available to stabilize at 550 p.p.m. (or above) exceeds the characteristic time of the global energy system. In **c** and **d** the vertical axis unit is percentage of 1990 gross world product (GWP), assuming the Nordhaus cost function[7]. Because $D = 50$ for all curves in **b**, **c** and **d**, uncertainties in the cost scale parameter $c_a(50)$ would only affect the curves in equal proportion.

and investment decisions made in the decade after the Second World War.

None of these additional sources of inertia are reflected in available 'integrated assessment' models. Such models do not explicitly represent energy-consuming infrastructure such as buildings or roads, or the linkages between different parts of supply systems. Nor do they capture issues of technology clustering (for example, the complex set of interlinked vehicle, fuel refining and delivery technologies required for modern transport) or adaptive responses associated with induced innovation, which cumulate over decades. Other critical aspects, such as the dynamics of population, economic growth and induced technology development and diffusion, within and beyond the energy sector itself, may also involve very long timescales, and these too are not captured in the current 'integrated assessment' models[15].

This difference between inertia in current modelling practice (~20 years) and the larger empirical value (~40–60 years) is therefore not surprising. Consequently we explore both 20 years and 50 years for the values of D; with these values, adjustment costs represent from 18% to 71% of the total cost, depending upon the situation (Table 1, Fig. 1c).

We focus initially on atmospheric concentration ceilings of 450 and 550 p.p.m.. CO_2 concentrations in the range 450–500 p.p.m., depending on assumptions about other greenhouse gases, correspond to a total radiative forcing about double the preindustrial CO_2 concentration, which has been the benchmark for most climate model analyses of future equilibrium climate change[11]. The higher value of 550 p.p.m. represents the level given greatest attention in ref. 12. Under the IPCC's IS92a emissions scenario (ref. 14) 450 p.p.m. will be passed around the year 2030, and our optimal scenarios converge to 450 p.p.m. as a ceiling in 2050–2060; 550 p.p.m. would be passed at around 2065 and converges as a ceiling in 2080–2100. Corresponding optimal pathways under different assumptions are illustrated in Fig. 1a. A value of 650 p.p.m. is not reached until the end of the century or even later.

Our main results regard the interaction of inertia and uncertainty for trajectories in which abatement can start from 1997. The top of Table 1 represents optimal trajectories to a concentration ceiling known from the start, whereas the bottom represents optimal strategies when 550 p.p.m. is the expected value of three equiprobable ultimate CO_2 concentration limits of 450, 550 or 650 p.p.m. (Fig. 1b). For deterministic ceilings, the optimal trajectory is most sensitive to the ceiling. Optimal global abatement in 2020 (over and above any 'no-regret' measures) ranges from 19% to 24% for the 450 p.p.m. ceiling, and 3% to 7% for the 550 p.p.m. case. When 550 p.p.m. is the average of a stochastic target, however, optimal abatement is 9–14%. Furthermore, the results are now quite sensitive to the assumed inertia. With $D = 50$ years, optimal global abatement in 2020 is 11–14%; only with low inertia and high discounting does it drop below 10%.

Table 1 Characteristics of optimal global emissions scenarios and strategies

Certainty scenario	D (years)	ρ	L (p.p.m.v.)	t_{stab}	x_{2020}	x_{2020} (equation 6a)	E_{max} (GtC)	$t_{E_{max}}$	Adj./total	Cost of delay
450A (Fig. 1a, c, d)	50	3%	450	2060	24%	18%	8.7	2015	59%	+70%
450B (Fig. 1a)	20	5%	450	2050	19%	14%	9.2	2015	32%	+32%
450C	50	5%	450	2050	20%	16%	9.1	2015	74%	+72%
450D	20	3%	450	2060	23%	19%	8.8	2015	19%	+25%
550A (Fig. 1a, b, c)	50	3%	550	2100	7%	4%	11.5	2050	55%	+10%
550B (Fig. 1a)	20	5%	550	2080	3%	2%	12.6	2050	31%	+2%
550C	50	5%	550	2090	4%	2%	12.2	2050	71%	+8%
550D	20	3%	550	2090	5%	4%	11.9	2050	18%	+3%
650A	50	5%	650	2125	3%	0%	14.1	2070	55%	+4%

Hedging strategy	D (years)	ρ	N	t_{info}	x_{020}	x_{2020} (equation 6a)	x_{2010}	E_{2020} GtC
U550A (Fig. 1b)	50	3%	3	2020	14%	15%	8%	9.6
U550B	20	5%	3	2020	9%	6%	4%	10.1
U550C	50	5%	3	2020	11%	12%	6%	9.9
U550D	20	3%	3	2020	12%	9%	7%	9.8
$U550L_{(late)}$	50	3%	3	2035	21%	17%	12%	8.9

Reduction figures refer to the global average (initial reductions focused on developed countries would be proportionately greater), and to reductions additional to those no incurring significant economic costs (that is, reductions beyond 'no regret' measures). Column t_{stab} shows the optimal stabilization date; x_{2020} shows the industrial-emissions abatement in 2020; (E_{max}, $t_{E_{max}}$) is the optimal emissions curve apex; Adj./total is the share of adjustment costs in total costs (see Fig. 1c, legend); the cost of delay is the increase in discounted total cost when reduction starts in 2020 instead of 1997; and E_{2020} is the optimal emissions level in 2020.

The explanation for this result is to be found in Table 1 and Fig. 1c, d. Under a deterministic 450-p.p.m. ceiling, the main early expenditures arise from the transitional costs of turning the system away from the reference trajectory; for $D = 50$ these amount up to 59% of the total discounted costs. Deferring abatement requires this effort to be squeezed into a much shorter period of time, as also demonstrated in ref. 13. Under the 450 p.p.m. ceiling, deferring abatement by two decades adds 70% to the total cost for $D = 50$, but only 32% for $D = 20$. As illustrated by the results for 550 p.p.m., the costs of deferring abatement is not nearly as large when the time to stabilization is much greater than the characteristic time of the socioeconomic system. Consequently, when the ultimate target is uncertain, the costs of switching to the 450-p.p.m. pathway too late far exceeds the costs of premature abatement in the 650-p.p.m. case. This effect is all the more important if the resolution of uncertainties comes later (scenario U550L).

Even with low inertia and high discounting, corresponding to most of the models cited in ref. 12, the abatement under uncertainty (U550B) is 9% in 2020 compared with 3% for the deterministic equivalent. But recognizing higher inertia and the extent of uncertainties amplifies the economic risks associated with deferring abatement.

The results of Wigley, Richels and Edmonds[12], drawing on various integrated assessment models of climate change such as DICE (ref. 8) or MERGE2 (ref. 9), have been widely interpreted to support a policy of modest early abatement. Our analysis, like theirs, neglects the role of early abatement in stimulating learning-by-doing (which would reduce subsequent abatement costs[4]) and in deferring and slowing the direct impacts of climate change itself. Even neglecting these benefits, our results show that abatement over the next few years is economically valuable if there is a significant probability of having to stay below ceilings that would otherwise be reached within the characteristic timescales of the systems producing greenhouse gases. With continuing growth in CO_2 emissions akin to the IS92a scenario, CO_2 concentrations are likely to exceed 500 p.p.m., equivalent to at least a doubling of preindustrial CO_2 levels even if other greenhouse-gas emissions are strongly controlled[12] within about 50 years. If there is a significant risk that we need to stay below this level, or if the 'business as usual' scenario is significantly higher over coming decades than the IS92a baseline we have assumed, then the socioeconomic inertia in energy systems in itself suggests that delay in abatement efforts may prove costly. □

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The uniform and low $^3He/^4He$ ratios of HIMU basalts as evidence for their origin as recycled materials

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Several hypotheses have been proposed for the origin of the group of lavas having the isotopic signature known as 'high μ' (HIMU, where $\mu = {}^{238}U/{}^{204}Pb$)[1–4]; these explanations have invoked processes involving recycled oceanic crust and sediment, metasomatically enriched subcontinental lithosphere, or intra-mantle metasomatism[1–12]. Here we present helium isotope analyses of HIMU basalts, with ages of 10–18 Myr, from three islands of the Cook–Austral Archipelago in the southern Pacific Ocean. We find that the HIMU samples have a relatively uniform and low $^3He/^4He$