The template peaks elute in the dimer region of the product oligo(G)s (not shown). Trimers were the longest oligomers formed when the templates were omitted from the reaction solution. The multiplicity of peaks observed, which had the HPLC retention times of tetramers and pentamers, suggests that the oligo(G)s formed have both 2′,5′ and 3′5′ links. The synthesis of the complementary 2′,5′-linked oligomers from a 3′,5′-linked template has been reported[20]. The converse process would proceed through a similar intermediate which contains hydrogen-bonded 2′,5′- and 3′,5′-linked oligomers[21–23].

It can be concluded from our studies that heterogeneous oligo(C)s formed by montmorillonite catalysis, or by almost any other chemical process[24], could have initiated the formation of complementary oligomers on the primitive Earth. The absence of regiospecificity in template-directed synthesis raises the question of how ribozymes with defined structures formed on the primitive Earth. One possibility is that catalysis of template-directed synthesis by minerals or metal ions resulted in greater regiospecificity[8]. In addition, some of the oligomers in the heterogeneous mixture formed by prebiotic processes could have catalysed the process of template-directed synthesis. This autocatalytic process would have selectively amplified the amounts of this catalytic RNA. Efficient ribozyme catalysts, which presumably had defined sequences, evolved from these initial transcripts[25–27]. □

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Economic and environmental choices in the stabilization of atmospheric CO_2 concentrations

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The ultimate goal of the UN Framework Convention on Climate Change is to achieve "stabilization of greenhouse-gas concentrations...at a level that would prevent dangerous anthropogenic interference with the climate system". With the concentration targets yet to be determined, Working Group I of the Intergovernmental Panel on Climate Change developed a set of illustrative pathways for stabilizing the atmospheric CO_2 concentration at 350, 450, 550, 650 and 750 p.p.m.v. over the next few hundred years[1,2]. But no attempt was made to determine whether the implied emissions might constitute a realistic transition away from the current heavy dependence on fossil fuels. Here we devise new stabilization profiles that explicitly (albeit qualitatively) incorporate considerations of the global economic system, estimate the corresponding anthropogenic emissions requirements, and assess the significance of the profiles in terms of global-mean temperature and sea level changes. Our findings raise a number of important issues for those engaged in climate-change policy making, particularly with regard to the optimal timing of mitigation measures.

The IPCC Working Group I (WGI) concentration profiles (S350–S750; Fig. 1) were constructed under the following constraints: (1) prescribed initial (1990) concentration and rate of change of concentration; (2) a range of prescribed stabilization levels and attainment dates; and (3) the requirement that the implied emissions should not change too abruptly. Inverse calculations

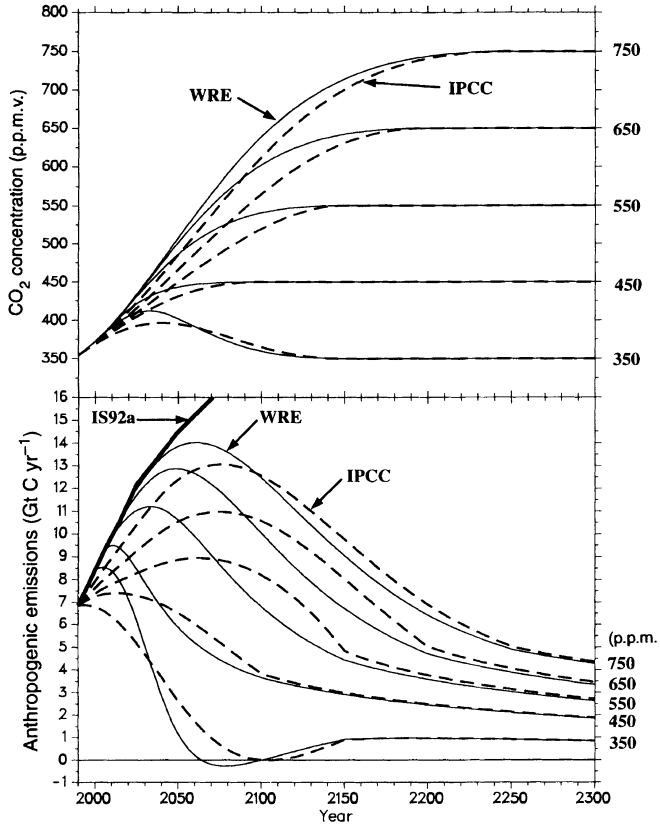

FIG. 1 Top, IPCC WGI[1,2] (dashed lines) and revised concentration profiles (WRE (this paper), solid lines) for stabilization of CO_2 at 350–750 p.p.m.v. Bottom, implied anthropogenic emissions using the model of Wigley[5]. IS92a is shown (thicker line) for comparison. Emissions were calculated following the procedure in ref. 1 in which the terrestrial biosphere sink is characterized solely by CO_2 fertilization of net primary productivity. The implications of using CO_2 fertilization as the sole terrestrial sink are discussed in ref. 4. The post-1990 inverse calculations were initialized by specifying a value for the 1980s-mean net deforestation (D_n80s). This determines the magnitude of the CO_2 fertilization factor. In the calculations in refs 1 and 2, D_n80s was taken as 1.6 Gt C yr^{-1}. This value has subsequently been revised downwards to 1.1 Gt C yr^{-1} (ref. 2), the value used here. Other minor budget changes have been made to accord with most recent data.

were then used to determine the emission rates required to achieve stabilization via the specified pathways. These show that stabilization requires an eventual and sustained reduction of emissions to substantially below current levels. Furthermore, some have interpreted the results for the IPCC pathways to imply that an immediate reduction in emissions (relative to the central IPCC "existing policies" or "business as usual" emissions scenario, IS92a[3]) is required to achieve any of the stabilization targets.

The WGI analysis was not intended as a recommendation for policy, but it will be carefully scrutinized for its policy implications. Consequently, it is important to understand what the analysis does and does not tell us. The first conclusion of the IPCC analysis, that meeting any of the prescribed targets will require emissions to decline eventually to levels well below today's, is robust. One cannot conclude from the WGI results, however, that an immediate reduction in emissions is required if we are to stabilize concentrations at 750 p.p.m.v. or below. The WGI emissions results correspond to just one of a range of possible pathways toward a particular concentration target. Stabilization at the same level, via different concentration routes, would produce different emissions.

What therefore are appropriate criteria for selecting a concentration (and hence emissions) time-path? Some guidance is found in the Framework Convention itself. Article 3 states that "policies and measures to deal with climate change should be cost-effective so as to ensure global benefits at the lowest possible cost". Thus, if two paths were indistinguishable in terms of their environmental implications, then the path with the lower mitigation (that is, emissions reduction) costs would be preferred. If two paths differed in terms of their environmental impacts, the issue becomes one of balancing benefits and costs. Here we examine alternative pathways for meeting the prescribed concentration targets. We then consider both the economic (costs) and environmental (benefits) implications of choosing one concentration trajectory over another.

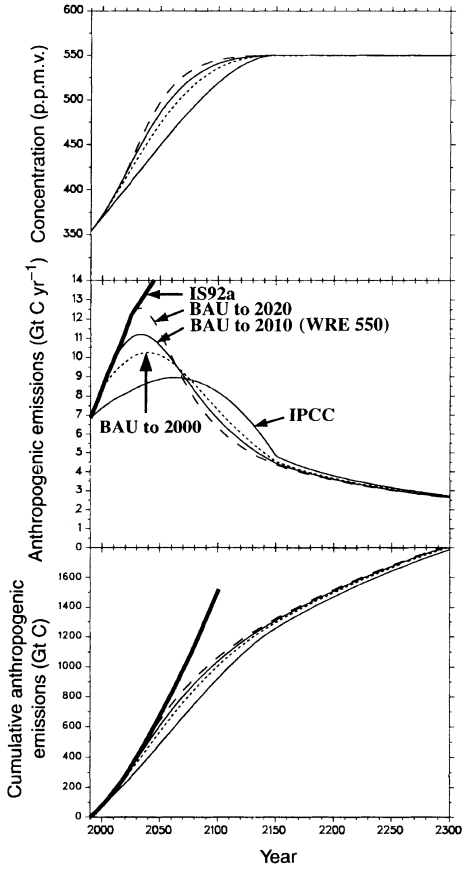

FIG. 2 Comparison of different concentration pathways (top panel) and implied emissions (middle) for stabilization of CO_2 levels at 550 p.p.m.v. in AD 2150. The pathways are: the original IPCC WGI S550 case[1]; the revised profile shown in Fig. 1 based on following BAU background emissions for 20 years, from 1990 to 2010 (WRE 550); and alternative revised profiles in which BAU is followed by 10 (BAU to 2000) or 30 years (BAU to 2020). The bottom panel shows the corresponding cumulative emissions. IS92a values are shown for comparison (thicker dashed lines).

In revising the IPCC WGI profiles, we add an additional constraint to the three noted above: that the resulting emissions trajectories initially track a 'business as usual' (BAU) path. This is an idealization of the assumption that the initial departure from BAU would be slow. We also assume that the higher the concentration target, the longer the adherence to BAU. This produces quite different concentration pathways, complementing the ones defined by IPCC WGI.

If we constrain emissions to follow BAU initially, the required concentration paths must depend on what we assume for this baseline scenario. We concentrate here on results for the central IPCC scenario (IS92a[3]). A higher baseline (such as IS92e or f) will lead to higher initial emissions. For a lower baseline such as IS92c, the task of stabilization of CO_2 concentrations at a level around 500 p.p.m.v. would require little action[4]. To derive the new profiles, we followed IS92a concentrations for 10–30 years and then fitted a smooth curve to the stabilization levels and dates used in ref. 1, using the same Padé approximant method. Figure 1 compares the new profiles with the WGI profiles. Further details are given in ref. 4.

The emissions implied by these new pathways (Fig. 1, lower panel) were obtained using the model of Wigley[5]. Although the precise values are model-specific, as shown by the inter-model comparison of Enting *et al.*[1], the qualitative character of the results and the relative differences in emissions due to concentration pathway differences are not.

The WGI analysis suggests that an immediate departure from the BAU path is required to meet all CO_2 concentration targets. Figure 1 shows that this is not so for concentration targets of 450 p.p.m.v. and above. Furthermore, for targets of 550 p.p.m.v. and above, the maximum rates of emissions decline are similar in both the new and WGI cases (but more prolonged in the former).

Figure 2 compares the old (WGI) and new results in more detail for the 550 p.p.m.v. stabilization case, and assesses the sensitivity of the results to the length of the interval over which BAU emissions are followed. The upper panel shows the WGI pathway and revised pathways following BAU for 10, 20 and 30 years (the 20-year case is that considered earlier). The emissions differences (middle panel) are striking in terms of the implied carbon intensity of the global energy system in the early decades of the next century. The different cumulative emissions pathways diverge initially and then become nearly parallel as one approaches and moves beyond the stabilization point (AD 2150 in this case). Cumulative emissions are noticeably higher in the cases that follow IS92a initially (a result that applies to all stabilization levels). This is because the products of early emissions have a longer time to be removed from the atmosphere, and because the associated higher concentrations give stronger oceanic and terrestrial sinks. Thus, later emissions reductions allow greater total CO_2 production, particularly for higher stabilization levels. These cumulative emissions differences, not considered by IPCC[2], may have important economic implications.

We now turn to how mitigation costs might vary with the choice of concentration profile. The rising emissions baseline that we use corresponds to an assumption that, in the absence of policy intervention, CO_2 emissions will continue to grow. This is consistent with the overwhelming majority of studies recently reviewed by the IPCC[6]. The implication is that stabilizing concentrations will entail some positive mitigation costs. A growing baseline, however, does not imply the absence of "no regrets" emissions reduction options (that is, with zero or negative mitigation costs). Such options are typically included in sizeable

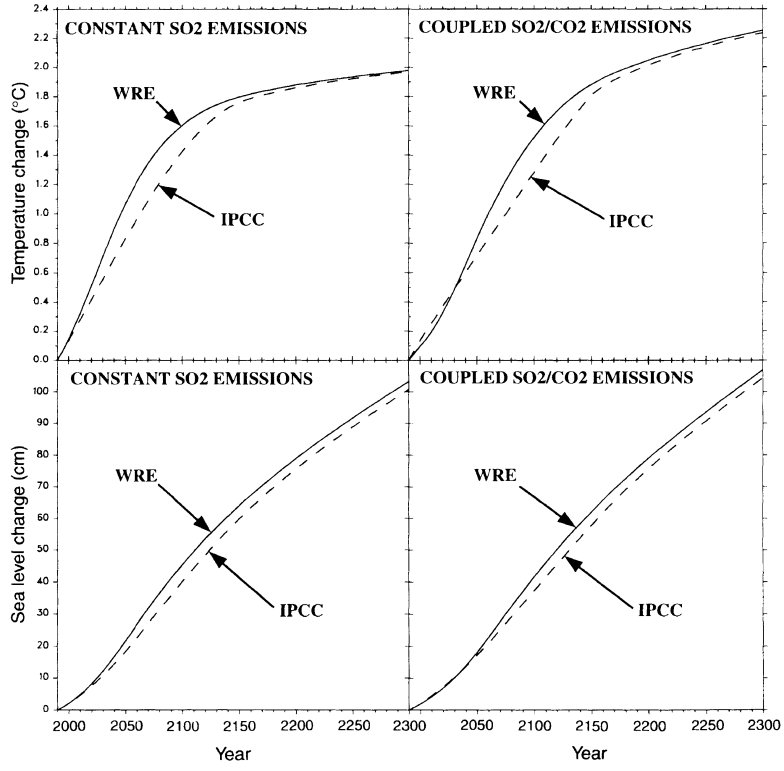

FIG. 3 Global-mean temperature (upper panels) and sea level changes (lower panels) for the S550 and WRE550 concentration stabilization pathways shown in Fig. 1. Results are from the models used in ref. 17, using the latest IPCC WGI estimate of the radiative forcing to 1990 and best-guess values of the climate sensitivity and ice-melt model parameters. Sea level changes include the contributions from oceanic thermal expansion, and ice melt from the world's glaciers and small ice caps, Greenland, and Antarctica. For the left panels, SO_2 emissions are held constant at their 1990 level. For the right panels, the effects of changes in anthropogenic SO_2 emissions (S) are added, with these changes directly coupled to those of fossil CO_2 emissions (F; values from Fig. 1) using $S = [S(1990)/F(1990)]F$. In both cases, the effects of non-CO_2 greenhouse-gases are accounted for by scaling CO_2 forcing by 1.33, the mean scaling for the IS92 emissions scenarios (compare ref. 21).

quantities in most economic analyses[7,8]. A growing baseline only means that economically competitive low-carbon alternatives are in insufficient supply to arrest future growth in carbon emissions. Conversely, if one were to assume that there are ample no-cost options to produce a falling emissions baseline, stabilization would entail little if any mitigation costs[9].

Several analysts have studied how mitigation costs might vary with the timing of the emissions reductions. For example, Nordhaus[10] and Manne and Richels[11] have identified cost-effective mitigation strategies for meeting a range of concentration targets. These studies show that to maintain cost-effectiveness, emissions tend to adhere longer to BAU the higher the concentration target (as assumed *a priori* here). Richels and Edmonds[12], in examining alternative emissions reduction pathways for stabilization at 500 p.p.m.v., found that the pathway can be just as important as the concentration stabilization level in determining the ultimate cost. Pathways involving modest reductions below a BAU scenario in the early years followed by sharper reductions later on were found to be less expensive than those involving substantial reductions in the short term. A similar conclusion can be found in Kosobud *et al.*[13].

Viewing the stabilization issue as a carbon budget allocation problem helps explain why concentration pathways with higher near-term emissions have lower overall mitigation costs. Because cumulative emissions are approximately independent of the concentration pathway, for each stabilization level there is, roughly, a fixed allowable amount of CO_2 to be released. The basic choice is, therefore, how this budget is to be allocated over time. From this perspective, the reasons for drawing more heavily on the budget in the early years are: (1) *Positive marginal productivity of capital.* With the economy yielding a positive return on capital[14], the further in the future an economic burden (here, emissions reduction) lies, the smaller is the set of resources that must be set aside today to finance the burden. (2) *Capital stock.* Stock for energy production and use is typically long-lived (for example, power plant, housing and transport). The current system is configured based upon a set of expectations about the future. Unanticipated changes will be costly. Time is therefore needed to reoptimize the capital stock. (3) *Technical progress.* There is ample evidence for past and potential future improvements in the efficiency of energy supply, transformation and end-use technologies. Thus, the availability of low-carbon substitutes will probably improve and their costs reduce over time. In addition, as the emissions budget will be somewhat larger (that is, greater cumulative emissions) for pathways with higher emissions earlier, dependence on higher-cost, carbon-free alternatives is reduced.

We must stress that, even from the narrow perspective of a cost-effectiveness analysis, our results should not be interpreted as suggesting a "do nothing" or "wait and see" policy. First, all stabilization pathways still require future capital stock to be less carbon intensive than under a BAU scenario. As most energy production and use technologies are long-lived, this has implications for current investment decisions. Second, new supply options typically take many years to enter the market place. To ensure sufficient quantities of low-cost, low-carbon substitutes in the future requires a sustained commitment to research, development and demonstration today. Third, any available "no regrets" measures for reducing emissions should be adopted immediately. Last, it is clear from Fig. 1 that one cannot go on deferring emissions reductions indefinitely, and that the need for substantial reductions of emissions is sooner the lower the concentration target.

It is, of course, also important to examine the environmental consequences of selecting one concentration or emissions trajectory over another. This is because different concentration pathways imply, not only different emissions reduction costs, but also different benefits in terms of averted environmental impacts. In benefit-cost analyses of climate change policy options, it is common to use global-mean temperature and sea level rise as coarse indicators of the extent of climate impacts[14,15]. We therefore calculate how these indicators are affected by differences in the pathways to stabilization at an atmospheric CO_2 concentration of 550 p.p.m.v., based on the model of Wigley and Raper[16,17]. We first consider the direct effects of greenhouse-gas concentration changes, and then how these results may be modified by SO_2 emissions. All results use the central IPCC-recommended estimate of climate sensitivity[18] (2.5 °C equilibrium global-mean warming for a doubling of atmospheric CO_2 levels) and best-guess ice-melt model parameters[17].

Figure 3 (left panels) shows that, if greenhouse gases alone are considered, both temperature change and sea level rise would be

noticeably affected by the choice of pathway towards stabilization at 550 p.p.m.v. These results, however, depend critically on how SO_2 emissions are assumed to change in the future. For the greenhouse-gas-alone case, we have assumed these emissions to remain constant at their 1990 level. As an alternative, we also consider a case where SO_2 emissions are closely coupled to fossil-fuel-derived CO_2 emissions. This case is consistent with the IPCC (IS92) emissions scenarios, except for IS92d, out to at least 2050 (ref. 3). It could occur if developing countries were less successful than developed countries in decoupling SO_2 and CO_2 emissions. In global-mean terms, SO_2/CO_2 emissions coupling leads to compensation between the reduced warming from reduced CO_2 emissions and an increased warming due to reduced SO_2 emissions[19,20].

To demonstrate the significance of this link, we give a specific example. This example is not meant to provide quantitative information on environmental impacts (which, for climate change, cannot be achieved through global-mean temperature alone), but to draw attention to aerosol influences as a critical factor in assessing the benefit–cost balance. Figure 3 compares global-mean temperature and sea level results for constant SO_2 emissions (left panels) with those for directly coupled CO_2 and SO_2 emissions (right panels). With SO_2 coupling, the lower-emissions case (S550) actually has warmer temperatures out to around 2040. This is because the much shorter lifetime of aerosols leads to a more rapid radiative forcing response to SO_2 emissions changes than to CO_2 emissions changes, allowing the former to dominate initially (compare refs 19,20). For sea level, coupling has a similar but less marked effect.

The market (for example, agriculture, timber and fisheries) and non-market (for example, biodiversity, environmental quality and human health) implications of these results are unclear: do pathway-related differentials up to ~0.2 °C in global-mean temperature and 4 cm in global-mean sea level change translate into significantly higher damages and, if so, are these large enough to offset the reduced cost of a more economical transition away from fossil fuels? The answer depends on the regional details associated with these changes, and the sensitivities of impact categories to changes in important climate variables. Both aspects are highly uncertain. Nevertheless, it is clear that the choice of emissions path requires the consideration of both costs and benefits. □

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Brief interstadial events in the Santa Barbara basin, NE Pacific, during the past 60 kyr

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THE instability of the Northern Hemisphere glacial climate over the past 100 kyr has been revealed by at least 20 brief warm (interstadial) episodes, called Dansgaard–Oeschger events, recorded in Greenland ice cores[1–3] and in North Atlantic sedimentary records[4,5]. A few of these events have been recognized elsewhere[6–8]. Here we describe a record of ocean oxygenation and circulation from the Santa Barbara basin in the northeast Pacific Ocean which correlates well with the Greenland ice-core records. We see 19 of the 20 Dansgaard–Oeschger events, in the form of laminated sediments deposited under anoxic conditions, and we can correlate at least 16 of these with the 17 ice-core interstadials of the past 60 kyr. Thus, these short-term events were not restricted to the North Atlantic region. The events had substantial ecological and oceanographic effects in the Santa Barbara basin, including changes in benthic faunal populations and in the age and composition of bottom waters. Similar ventilation changes have been seen in the Gulf of California[9,10], suggesting that these changes may have been widespread and synchronous along the northeast Pacific margin. These results suggest sensitivity of broad areas of the ocean–atmosphere–cryosphere system to short-term climate change.

It is now generally accepted that switches in Quaternary climate conditions occurred at much shorter timescales than the orbitally modulated, 20 k to 100-kyr Milankovich-band cycles of insolation[1–3]. Changes in temperature on millennial timescales are asymmetric, with abrupt, decadal-timescale warming followed by gradual cooling[1]. To preserve records of such short-term fluctuations in the marine environment requires special conditions. Late Quaternary sedimentation rates in the Santa Barbara basin ($> 120\,cm\,kyr^{-1}$) are >10 times higher than those typical of the deep sea, and owing to its geographical and bathymetric configuration the benthic environment is highly sensitive to climate and oceanographic changes, thus making this sequence well suited to the recording of changes at ultra-high resolution. The Santa Barbara basin is a confined, silled basin in the inner Continental Borderland of southern California[11]. The modern basin is ~ 600 m deep and opens over a deep (~475 m) sill to the Pacific and a shallower (~230 m) sill to the adjacent Santa Monica basin. It contains oxygen-depleted waters below sill-depth, derived from the upper part of intermediate waters and the oxygen-minimum zone off central California (with 0.4–0.7 $ml\,l^{-1}$ O_2 at 500 m depth[12]). This source water is further depleted of oxygen (< 0.1 $ml\,l^{-1}$ O_2) by degradation of organic matter from surface productivity (ref. 12). Oxygen deficiency excludes benthic macrofauna and prevents bioturbation[13], so that below ~525 m seasonal variations in sediment supply (siliciclastic versus planktonic biogenic components) are preserved in the mud as thin, millimetre-scale laminations or

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