Abstract. A coupled carbon cycle-climate model is used to compute global atmospheric CO\textsubscript{2} and temperature variation that would result from several future CO\textsubscript{2} emission scenarios. The model includes temperature and CO\textsubscript{2} feedbacks on the terrestrial biosphere, and temperature feedback on the oceanic uptake of CO\textsubscript{2}. The scenarios used include cases in which fossil fuel CO\textsubscript{2} emissions are held constant at the 1986 value or increase by 1\% yr\textsuperscript{-1} until either 2000 or 2020, followed by a gradual transition to a rate of decrease of 1 or 2\% yr\textsuperscript{-1}. The climatic effect of increases in non-CO\textsubscript{2} trace gases is included, and scenarios are considered in which these gases increase until 2075 or are stabilized once CO\textsubscript{2} emission reductions begin. Low and high deforestation scenarios are also considered. In all cases, results are computed for equilibrium climatic sensitivities to CO\textsubscript{2} doubling of 2.0 and 4.0 °C.

Peak atmospheric CO\textsubscript{2} concentrations of 400–500 ppmv and global mean warming after 1980 of 0.6–3.2 °C occur, with maximum rates of global mean warming of 0.2–0.3 °C decade\textsuperscript{-1}. The peak CO\textsubscript{2} concentrations in these scenarios are significantly below that commonly regarded as unavoidable; further sensitivity analyses suggest that limiting atmospheric CO\textsubscript{2} to as little as 400 ppmv is a credible option.

Two factors in the model are important in limiting atmospheric CO\textsubscript{2}: (1) the airborne fraction falls rapidly once emissions begin to decrease, so that total emissions (fossil fuel + land use-induced) need initially fall to only about half their present value in order to stabilize atmospheric CO\textsubscript{2}, and (2) changes in rates of deforestation have an immediate and proportional effect on gross emissions from the biosphere, whereas the CO\textsubscript{2} sink due to regrowth of forests responds more slowly, so that decreases in the rate of deforestation have a disproportionately large effect on net emission.

If fossil fuel emissions were to decrease at 1–2\% yr\textsuperscript{-1} beginning early in the next century, emissions could decrease to the rate of CO\textsubscript{2} uptake by the predominantly oceanic sink within 50–100 yrs. Simulation results suggest that if subsequent emission reductions were tied to the rate of CO\textsubscript{2} uptake by natural CO\textsubscript{2} sinks, these reductions could proceed more slowly than initially while preventing further CO\textsubscript{2} increases, since the natural CO\textsubscript{2} sink strength decreases on time scales of one to several centuries. The model used here does not account for the possible effect on atmospheric CO\textsubscript{2} concentration of possible changes in oceanic circulation. Based on past rates of atmospheric CO\textsubscript{2} variation determined from polar ice cores, it appears that the largest plausible perturbation in ocean-air CO\textsubscript{2} flux due to changes of oceanic circulation is substantially smaller than the permitted fossil fuel CO\textsubscript{2} emissions under the above strategy, so tying fossil fuel emissions to the total sink strength could provide adequate flexibility for responding to unexpected changes in oceanic CO\textsubscript{2} uptake caused by climatic warming-induced changes of oceanic circulation.

1. Introduction

The atmospheric concentration of CO\textsubscript{2} and other greenhouse gases is expected to
increase significantly over the next few decades and to lead to large and essentially irreversible changes of climate. It is often regarded as an established fact that atmospheric CO$_2$ concentration will eventually double, the only question being when this doubling will occur. Most recent carbon cycle model studies of possible future CO$_2$ concentrations assume fossil fuel CO$_2$ emissions to grow exponentially at rates ranging from 0.3% yr$^{-1}$ to 3.0% yr$^{-1}$ (i.e.: Goudriaan and Ketner, 1984; Trabalka et al., 1986) or assume that the entire recoverable fossil fuel resource will be consumed following a logistic curve (i.e.: Bacastow and Bjorkstrom, 1981; Killough and Emanuel, 1981; Viecelli et al., 1981; Siegenthaler, 1983).

Some studies consider scenarios in which CO$_2$ emissions decrease (Perry et al., 1982; Laurmann and Spreiter, 1983; Khandani and Rose, 1985; Perry, 1986; Maier-Reimer and Hasselmann, 1987). Ekdahl and Keeling (1973) had showed that, for an exponential increase of CO$_2$ emissions with an invariant time constant $\mu$, the airborne fraction (the fraction of emitted CO$_2$ remaining in the atmosphere) is approximately constant after a few multiples of $\mu$ for linear models. Perry (1986) argued that the error introduced by assuming a constant airborne fraction for scenarios in which CO$_2$ emissions begin to decrease is small, even for scenarios leading to CO$_2$ ceilings as low as 500 ppmv. However, results of Maier-Reimer and Hasselmann (1987) and discussion by Firor (1988) indicate that the ocean will take up an increasingly larger fraction of emitted CO$_2$ as emissions decrease, corresponding to a decrease of the airborne fraction.

Numerous studies have shown that substantial reductions in total energy use, and hence in CO$_2$ emissions, are possible in the industrialized world through improved efficiency of energy use, and that the third world need not follow the industrialized world's path of high energy use as it undergoes development (see Lovins, 1980; Cheng et al., 1986; Goldemberg et al., 1985, 1988; Johansson and Williams, 1987; Chandler, 1988; Johansson et al., 1989; and references therein). In particular, Goldemberg et al. (1985, 1988) show that in a world of 7 billion people by 2030, the third world could be brought to a Western European standard of living and the industrialized world's per capita primary energy use reduced by 50%, for an increase of global primary energy demand of only 10%.$^1$

Given the tremendous scope for reducing CO$_2$ emissions below what they would otherwise be by improving energy efficiency, the further decreases possible through increased use of non-fossil fuel energy sources (see Harvey, 1989a), and the tendency of the airborne fraction to decrease as CO$_2$ emissions decrease, it is pertinent to examine the impact on atmospheric CO$_2$ concentration of a number of CO$_2$ emission reduction scenarios. To do this, we use a coupled climate-carbon cycle model which includes the additional forcing attributable to the buildup of other greenhouse gases.

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$^1$ Although total primary energy demand (commercial + non-commercial) increases by only 10%, commercial primary energy demand increases by 30% globally and by 120% in the developing world according to this scenario.