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ABSTRACT

The burning of biomass that often accompanies deforestation and other changes in land use is believed to be a major contributor to documented increases in the concentration of atmospheric CO_2. Using three models of carbon turnover in the atmosphere and ocean, we simulate changes in atmospheric CO_2 that result from the addition of CO_2 from industrial sources and terrestrial ecosystems disturbed by changes in land use. We simulate atmospheric response to different histories of terrestrial biospheric CO_2 release, and we compare these simulations with the history of atmospheric CO_2 obtained from ice core measurements and atmospheric monitoring stations. Our results reinforce previous conclusions that the *Houghton et al.* [1983] population-based estimate of the history of terrestrial biospheric CO_2 release is incompatible with the historical record of atmospheric CO_2 and conventional models of oceanic uptake of CO_2. The simulations overestimate observed atmospheric CO_2 concentrations and the rate of change in concentration. Recent estimates of the history of terrestrial biosphere CO_2 release made with a modification of the Houghton et al. model and revised data on land use change and ecosystem carbon do not adequately resolve the incompatibility. Histories of net terrestrial biosphere-atmosphere CO_2 exchange obtained by deconvolution of atmospheric CO_2 data necessarily provide the desired agreement between simulation and observation, but the deconvolved estimates differ qualitatively from the histories generated by the Houghton et al. historical-ecological model. The latter indicates that for the past several decades the terrestrial biosphere has been an increasing source of atmospheric CO_2, whereas the deconvolutions imply that the terrestrial biosphere has been a declining source and even a global sink for atmospheric CO_2. Uncertainty about the past behavior of the terrestrial biosphere contributes as much uncertainty to the projection of future changes in atmospheric CO_2 as uncertainty about CO_2 release from future changes in land use.

INTRODUCTION

The recent increase in the tropospheric concentration of CO_2 is well documented. Observations from monitoring stations at Mauna Loa, Hawaii, and elsewhere record an increase of approximately 11% over the past 30 years [*Gammon et al.*, 1986; *Keeling et al.*, 1989], and measurements from air trapped in old ice at Siple Station, Antarctica, indicate an increase of 26% since the middle of the 18th century [*Neftel et al.*, 1985; *Friedli et al.*, 1986].

The causes of this increase are less certain than the observed change, but it is agreed that the release of CO_2 to the atmosphere during the combustion of fossil fuels (i.e., the burning of fossil biomass) is a major contributor. The increase in tropospheric CO_2 is concurrent with the documented increase in global use of fossil fuels and the consequential increase in the release of CO_2 to the atmosphere [*Keeling*, 1973b; *Marland and Rotty*, 1984]. The burning of biomass that accompanies deforestation and other changes in land use, including the rapid combustion of fuelwood and fires used in land clearing as well as the slow oxidation of decomposition, is also believed to release significant amounts of CO_2 to the atmosphere. However, the relative contribution of this source to observed changes is even less certain than that of fossil fuels.

Part of the uncertainty has its origin in the observation that only a fraction of the CO_2 released in the combustion of fossil fuels is retained by the atmosphere. The 35 μL L^{-1} (or 75 Gt C) increase in tropospheric CO_2 over the period of the Mauna Loa record (1959–1988) is equivalent to approximately 58% of the total CO_2 released from industrial sources during that same period (129 Gt C, 96% of which is from fossil fuels [*Marland et al.*, 1989]). If the observed CO_2 increase during this period were due solely to industrial sources, the biogeochemical dynamics of the earth's global carbon cycle would have had to redistribute approximately 42% of the industrial CO_2 emissions to oceanic and terrestrial reservoirs. Conventional models of CO_2 uptake by the ocean account for about 25–35% of fossil-fuel CO_2 emissions from the period 1958–1980 [*Peng*, 1986], a shortfall of 7-17% that

must be accounted for elsewhere. The terrestrial biosphere is a reasonable candidate, but the capacity of global terrestrial ecosystems to sequester the required amounts of CO_2 over that period of time is controversial, and recent work by *Tans et al.* [1990] suggests that oceanic uptake may be more on the order of 20% of industrial CO_2 emissions, requiring even greater sequestering by terrestrial ecosystems. It is difficult to account for any significant addition of CO_2 to the atmosphere from land-use change when current understanding of the global carbon cycle is unable to fully account for industrial CO_2 emissions alone. Thus, in the face of evidence for recent increases in the rates of tropical deforestation [*Houghton*, 1990] and presumably some nontrivial release of CO_2 to the atmosphere, the contribution of terrestrial ecosystems to observed changes in atmospheric CO_2 is uncertain and problematic. The uncertainty is compounded by difficulties inherent in reconstructing the history of CO_2 release that may have accompanied past changes in land use.

For example, the history of CO_2 release from land-use change can be inferred by deconvolution of data recording the history of changes in the global carbon cycle. In one approach, the equation representing changes in the mass of atmospheric CO_2

$$\frac{dc_a}{dt} = F_i + F_r - F_{as} \tag{1}$$

is solved for the unknown or residual flux F_r, where c_a is the observed mass of atmospheric CO_2, F_i is the known flux of CO_2 to the atmosphere from industrial sources, and F_{as} is the net CO_2 flux from the atmosphere to the ocean calculated by an appropriate carbon cycle model [*Killough and Emanuel*, 1981; *Siegenthaler and Oeschger*, 1987; *Keeling et al.*, 1989]. Similar formulations can be derived for changes in carbon isotope ratios, and other approaches or formalisms are possible [e.g., *Oeschger and Heimann*, 1983; *Enting and Pearman*, 1986; *Enting and Mansbridge*, 1987; *Keeling et al.*, 1989].

By assuming that (1) completely describes the atmosphere's CO_2 balance, that all anthropogenic CO_2 emissions are distributed among atmosphere, ocean, and terrestrial biosphere reservoirs, and that F_{as} completely describes net oceanic uptake, the residual

flux, F_r, can be interpreted as net flux between the atmosphere and the terrestrial biosphere. By assuming no net atmospheric CO_2 exchange with terrestrial ecosystems that have not been disturbed by land-use change, the residual flux can be interpreted as an estimate of the net terrestrial biospheric CO_2 exchange due to changes in land use.

Unfortunately, these interpretations are confounded by the potential for error in the carbon cycle models used to calculate F_{as} and potential error in the history of industrial CO_2 emissions used to define F_i [*Killough and Emanuel*, 1981; *Siegenthaler and Oeschger*, 1987]. Error or uncertainty in either is reflected as error or uncertainty in the estimate of past terrestrial biospheric exchange. There is also the problem of error in the historical data being deconvolved, both atmospheric CO_2 concentrations and isotopic ratios. These same uncertainties impact estimates of terrestrial biosphere CO_2 release produced by deconvolution of changes in isotopic ratios recorded in tree rings [*Peng et al.*, 1983; *Emanuel et al.*, 1984; *Stuiver et al.*, 1984]. Tree-ring-based reconstructions are especially prone to limitations imposed by the intrinsic variability of tree-ring isotope records [*Freyer*, 1986].

Direct reconstruction of CO_2 release by explicit consideration of changes in land use and the response of carbon in soils and vegetation of affected ecosystems is preferable to inferential reconstructions by deconvolution. But here too there are limitations. There are no direct measurements of the CO_2 fluxes accompanying changes in land use at the spatial and temporal scales appropriate to large-scale land conversion (e.g., deforestation of the Amazonian basin). Thus, computer models are used to estimate CO_2 release to the atmosphere based on data that are available. These data include rates of land use change, the types of ecosystems affected, and carbon storage in vegetation and soils before and after the disturbance [*Revelle and Munk*, 1977; *Moore et al.*, 1981; *Houghton et al.*, 1983; *Richards et al.*, 1983; *Bogdonoff et al.*, 1985]. However, these data have high uncertainties, and their use contributes a great deal of uncertainty to the reconstruction of past land-use CO_2 release [*Houghton*, 1986]. It is difficult enough to estimate the amount of CO_2 released in a single year of the recent past for which relatively good data is available [*Detwiler et*

al., 1985; *Hall et al.*, 1985; *Houghton et al.*, 1985, 1987]. Reconstructing CO_2 release over the last 200–300 years, especially the timing of that release, is made even more difficult by the additional demands for historical data and the coincident increase in the uncertainty of those data. Consequently, there are vary few direct historical-ecological reconstructions of CO_2 release from past changes in land use, especially those that resolve the timing of that release [*Houghton*, 1986].

Nevertheless, it is precisely the history of past CO_2 release to the atmosphere, both the amounts and the timing, that is crucial to understanding past changes in atmospheric CO_2 and, consequently, to our ability to project future changes. As noted by *Siegenthaler et al.* [1978, p. 83], "If a large input pulse occurred only a few decades ago, it is still influencing the present CO_2 level by providing a decreasing atmospheric 'baseline', since excess CO_2 is still being taken up by the ocean. The longer ago such an input occurred, the smaller is its influence on the present trend."

The purpose of this paper is to examine how different histories of CO_2 release from changes in land use influence past and future changes in atmospheric CO_2. We first simulate the historical response of atmospheric CO_2 to alternative histories of land-use CO_2 release reconstructed with a historical-ecological model of land-use change and CO_2 release. We examine the impact of each history on the coincidence between simulated and observed atmospheric CO_2. We then compare these CO_2 release histories with histories reconstructed by deconvolution of the atmospheric CO_2 record. We conclude by exploring the implications of these deconvolved reconstructions for the simulation of future changes in atmospheric CO_2.

METHODS

The Models

We used three models of global carbon cycling between ocean and atmosphere (Figure 1). The first, an implementation of the *Oeschger et al.* [1975] box-diffusion model, is

referred to here as the box-diffusion model (Figure 1, model 1). The others are implementations of models described by *Killough and Emanuel* [1981]. The first of these is a layered ocean model that considers only diffusive fluxes of carbon in the ocean (Figure 1, model 2); the second uses the same ocean structure but considers advective as well as diffusive fluxes (Figure 1, model 3). These models are referred to here as the discrete-diffusion and discrete-advection models, respectively. Structurally, the discrete-diffusion and discrete-advection models correspond to models 3b and 3a, respectively, of *Killough and Emanuel* [1981].

Each model represents ocean-atmosphere carbon dynamics with a system of ordinary differential equations describing changes in carbon mass of the various reservoirs or model compartments. The three models differ only in their structural representation of the deep ocean and their representation of carbon flux within that structure (Figure 1). The models each have a 75-m well-mixed surface layer. The box-diffusion model has 42 subsurface layers of constant horizontal cross-sectional area, 37 layers of 25-m depth down to 1000 m (intermediate waters) and 5 layers of 560-m depth to the ocean floor. The discrete-diffusion and discrete-advection models have 18 subsurface layers with horizontal areas that vary with depth according to the hypsography of *Sverdrup et al.* [1942] [*Killough*, 1980; *Killough and Emanuel*, 1981]. The layer immediately below the surface layer is 50 m deep; the next is 75 m. The remaining eight layers of intermediate waters, to 1000 m, are 100 m in depth. The seven layers between 1000 m and 4500 m are 150 m deep; the bottommost layer extends from 4500 m to the ocean floor at greater than 7000 m.

The exchange of CO_2 between the atmosphere and the surface mixed layer of the ocean is governed by the difference between the partial pressures of CO_2 in the atmosphere and in sea surface waters. The partial pressure of CO_2 in the atmosphere is proportional to the ratio of the masses of CO_2 and dry air, whereas the partial pressure of CO_2 in surface waters depends on the chemical equilibria between carbon compounds. We model this chemical equilibration with the dynamic carbonate chemistry of *Takahashi et al.* [1980]. The result

is a nonlinear function $p_s(c_s)$ that expresses the dependence of the partial pressure of CO_2 dissolved in surface waters on the total carbon content of those waters. This relationship buffers the increase in surface water CO_2 relative to the increase in atmospheric CO_2. Our implementations of the *Killough and Emanuel* [1981] models differ slightly from previous implementations in our use of the *Takahashi et al.* [1980] formulation for sea surface carbonate chemistry rather than the *Keeling* [1973a] formulation. More importantly, our implementation of the box-diffusion model differs from the original *Oeschger et al.* [1975] implementation in that we use a dynamic nonlinear carbonate chemistry. *Oeschger et al.* represented sea surface buffering with a constant linear buffer factor.

Mixing and circulation remove carbon from the ocean's surface layer, transferring it to the deeper layers, where it may be sequestered for several hundred years [*Stuiver et al.*, 1983]. The box-diffusion model represents these subsurface fluxes as a system of ordinary differential equations describing the layered finite-difference approximation of the partial differential equation representing subsurface mixing as continuous vertical eddy diffusion [*Oeschger et al.*, 1975]. According to [*Siegenthaler*, 1983], the model's diffusion is best "regarded as a parameterized representation of the various processes of mixing and advection in the ocean, projected on a vertical axis."

The discrete-diffusion model represents the transport of carbon by diffusive mixing and particle flux through successive layers, both upward and downward, as first-order linear kinetics between neighboring layers. The discrete-advection model represents upward transport in the same way, but downward transport is represented by first-order linear kinetics between the surface layer and individual subsurface layers (Figure 1). This downward pathway represents the sinking of cold dense polar waters and the accompanying advective transport of carbon from the surface to the deep ocean [*Killough and Emanuel*, 1981].

The Simulations

Initial conditions. We assume initial conditions of a preindustrial steady-state carbon cycle. An initial atmospheric CO_2 concentration of 277 μL L^{-1} in 1745 is indicated by the Siple ice core record [*Neftel et al.*, 1985; *Friedli et al.*, 1986]. The assumption of steady-state atmosphere-ocean CO_2 exchange determines an equivalent partial pressure of dissolved CO_2 in the surface ocean. The corresponding mass of surface ocean carbon is calculated by solving the surface water equations for chemical equilibria between carbon compounds with specified initial conditions. Initial deep ocean carbon inventories and ^{14}C activities are as given in *Killough and Emanuel* [1981]. For the discrete-diffusion and discrete-advection models, transfer coefficients for the exchange of carbon between the atmosphere and the surface ocean and the flux of carbon between ocean layers are determined from the steady-state equations of carbon transfer and the assumed preindustrial carbon inventories and ^{14}C activities. Transfer coefficients for atmosphere-ocean CO_2 exchange and the diffusivity coefficient K of the box-diffusion model are determined from the steady-state carbon inventories and by fitting simulations of deep ocean ^{14}C to an idealized global preindustrial profile derived from observations of ocean ^{14}C prior to its extensive release in nuclear bomb testing [*Oeschger et al.*, 1975; *Broecker et al.*, 1985].

Anthropogenic emissions. The models are driven from their initial steady states by carbon added to the atmosphere from anthropogenic sources. For industrial CO_2 emissions (fossil fuels plus cement manufacturing), we used the history depicted in Figure 2. Emissions for 1950–1986 are those derived by *Marland et al.* [1989] from United Nations fuel production data and U.S. Department of Interior, Bureau of Mines, data on cement manufacturing. T. A. Boden (Carbon Dioxide Information and Analysis Center, Oak Ridge National Laboratory, personal communication, 1988) provided the emissions estimate for 1987 based on these same data sources. Fossil fuel CO_2 emissions for 1860–1949 are from *Keeling* [1973b, Table 14]. We estimated pre-1860 fossil fuel CO_2 emissions with *Keeling's*

[1973b, equation (6.1)] exponential extrapolation of the 1960-1949 data. Similarly, we estimated pre-1950 CO_2 emissions from cement manufacturing according to the exponential extrapolation of by *Keeling* [1973b, equation (6.2)].

We considered four different histories of CO_2 release from the anthropogenic conversion of terrestrial ecosystems from their natural states, or at least their preindustrial states, to forestry, agricultural production, or other uses. In the first, we simply assumed that there was in fact no net CO_2 release to the atmosphere from this biospheric source. The remaining histories (Figure 3) are from the work of *Houghton et al.* [1983] and *Houghton* [1989]. These histories are direct reconstructions based on historical land-use data. The models used in these reconstructions, the Marine Biological Laboratory Terrestrial Carbon Model [*Moore et al.*, 1981; *Houghton et al.*, 1983; *Houghton*, 1986] and its derivative [*Houghton*, 1989], describe the net release of carbon to the atmosphere that accompanies changes in land use by tracking yearly changes in area, age, and carbon content (vegetation and soil) of terrestrial ecosystems that have been disturbed by various types of land-use change (e.g., conversion from forest to cultivated land). The areas and ecosystems involved are estimated from a variety of statistics on wood harvest and changes in agricultural land. Harvested material is distributed among decay pools with residence times based on the different uses of the material, and the models calculate the subsequent annual loss of carbon from those pools. For example, fuelwood is accounted for in a decay pool with 1-year residence time. Changes in the amount of carbon in vegetation and soils following the land-use disturbance are calculated from idealized response curves that describe temporal changes in carbon mass per unit land area. The curves are parameterized by ecosystem type and type of land-use change, and they account for factors affecting both loss and accumulation of carbon without actually modeling processes such as photosynthesis, growth, mortality, and decomposition [*Moore et al.*, 1981; *Houghton et al.*, 1983]. For example, the impact of fires used in forest clearing is implicitly incorporated in response-curve parameters defining the amount of carbon in vegetation before and after clearing. The net

annual loss of carbon from the vegetation and soils of all ecosystem types and geographic regions plus the annual loss from the decay pools for harvested material is an estimate of annual global carbon release to the atmosphere from changes in land use. The models assume that there is no net exchange of carbon between the atmosphere and ecosystems not disturbed by land use change.

History A (Figure 3) is the population-based estimate of *Houghton et al.* [1983]. We estimated carbon release before 1825 by linear extrapolation from the 1825 value to zero release before 1770. We assumed constant release at the 1980 value for the period 1980–1987.

Histories B and C (Figure 3) are more recent estimates [*Houghton*, 1989] that incorporate revised estimates of land-use change, carbon stocks in tropical ecosystems, and the reduction in soil carbon following forest clearing [*Houghton et al.*, 1985, 1987]. History B is a high estimate based on medium-to-high estimates of tropical biomass; history C is the corresponding low estimate based on low estimates of tropical biomass. We estimated pre-1860 carbon release by linear extrapolation to zero release before 1770, and we assumed constant release at the respective 1985 values for 1986 and 1987.

A fraction of the carbon added to the atmosphere from the anthropogenic sources penetrates the ocean surface as CO_2 and is distributed throughout the ocean according to the dynamics of each model. The mass of carbon remaining in the atmosphere is converted to CO_2 concentration based on the molecular weights of carbon and air and the dry air mass of the atmosphere. The simulated history of change in atmospheric CO_2 concentration is then compared with the observed history specified by CO_2 measurements from the Siple Station, Antarctica, ice core [*Neftel et al.*, 1985; *Friedli et al.*, 1986] and the monitoring station at Mauna Loa Observatory, Hawaii, [*Keeling*, 1986]. (The Mauna Loa measurements approximate mean global concentrations within 0.2-0.3 μL L^{-1} [*Gammon et al.*, 1986].)

RESULTS AND DISCUSSION

Simulation of Past Changes (1750-1988)

If we first assume that historically the terrestrial biosphere has made no net contribution to atmospheric CO_2, we can simulate past changes in atmospheric CO_2 using only the history of industrial CO_2 emissions as atmospheric input. With these assumptions, the models all underestimate observed concentrations during most of the Siple period (ca. 1750–1960) and throughout the Mauna Loa period (ca. 1960–1990) (Figure 4). The greatest deviations from the observations occur at about the middle of this century. The models overestimate the rate of change in atmospheric CO_2 during the Mauna Loa period. Consequently, the differences between observations and simulations narrow during the latter years of the simulations (Figure 4). The simulations' overestimates of the change in atmospheric CO_2 during the Mauna Loa period are consistent with the problem of "missing" industrial CO_2 discussed in the introduction.

The box-diffusion model generates the smallest net uptake of CO_2 by the ocean and consequently yields the highest atmospheric concentrations, followed in turn by the discrete-diffusion model. The discrete-advection model with its more effective transfer of carbon to the deep ocean by advective flux has the largest net oceanic CO_2 uptake and yields the lowest atmospheric concentrations. Although the differences among models increase gradually with time, the differences are always less than those between observations and simulations. For example, in 1987 the difference in CO_2 concentrations simulated by the box-diffusion and discrete-advection models is 7 μL L^{-1} while their respective deviations from the Mauna Loa record are 9 μL L^{-1} and 16 μL L^{-1}.

If we assume no net input of carbon from natural sources, an underestimation of past CO_2 concentrations when CO_2 input is limited to industrial sources suggests the presence of a significant contribution from past changes in land use. An accurate estimate of the size and timing of that input is indicated by coincidence between observed and modeled CO_2 in simulations that include histories of both land-use and industrial emissions.

Figure 5 shows the correspondence, or rather lack of correspondence, between the observed atmospheric CO_2 record and our simulations combining the histories of land-use CO_2 release from Figure 3 with the industrial CO_2 emissions as atmospheric input. In each case the simulations overestimate concentrations during the Mauna Loa period. In the extreme, when we use the older estimate from *Houghton et al.* [1983] (history A, Figure 3), the models overestimate the 1987 concentration by 39–45 μL L^{-1} (Figure 5a). At best, when we use the low estimate of history C (Figure 3), the models overestimate the 1987 concentration by 9–20 μL L^{-1} (Figure 5c). For comparison, the change in concentration over the Mauna Loa period is approximately 35 μL L^{-1}.

Coincidence between simulation and observation is more variable during the Siple period than during the Mauna Loa period. Simulations with land-use emission history A do match the Siple record reasonably well until around 1900, when they diverge radically from the observations (Figure 5a). Simulations with histories B and C tend to slightly underestimate CO_2 concentrations until about 1900 and do reasonably well until about 1950; then they too diverge from the observations, overestimating the concentration and rate of change for the rest of the simulation (Figures 5b,c).

The pattern among models seen in the simulations without CO_2 from land-use change (Figure 4) is repeated in these simulations (Figure 5). The box-diffusion model produces the largest atmospheric CO_2 concentrations and, in these comparisons, the greatest deviation from the Mauna Loa observations. The discrete-advection model produces the lowest concentrations and, again in these comparisons, the closest agreement during the Mauna Loa period. The discrete-diffusion model is intermediate. As in the earlier simulations, the models slowly diverge from one another with time. Note also that the differences among models and the differences attributable to land-use emission history overlap. Simulated atmospheric CO_2 from the discrete-advection model using emission history B approximates the simulation using the box-diffusion model and emission history C (Figures 5b,c). To

a lesser extent, this is also true for the discrete-advection model using history A and the box-diffusion model using history B (Figures 5a,b).

The improvement in coincidence between observation and simulation with the changes from land-use emission history A to history C is due principally to a change in the amount of CO_2 released from past changes in land use rather than to the timing of that release. Except for nearly constant or slightly declining CO_2 releases from ca. 1920–1945 in histories B and C compared with the increasing release for that period in history A, the pattern or timing of CO_2 release does not differ appreciably among the alternative emission histories (Figure 3). Furthermore, the difference between histories B and C and the accompanying improvement in correspondence between observation and simulation when history C is used (Figure 5c) are due to the lower estimates of tropical biomass used in producing history C.

Clearly, understanding of past global carbon cycle dynamics as summarized in the models and emission histories we use here is incomplete. Somewhere, either singly or in some combination, errors in the record of past CO_2 concentrations, the reconstruction of past industrial CO_2 emissions, the understanding and modeling of ocean-atmosphere carbon dynamics, or the understanding of terrestrial biospheric sources and sinks (including the reconstruction of past CO_2 release from changes in land use) are large enough to produce the level of disagreement between observation and simulation seen here and elsewhere [*Peng et al.*, 1983; *Enting and Pearman*, 1986; *Enting and Mansbridge*, 1987; *Keeling et al.*, 1989]. For our present purpose we assume that errors in the record of past CO_2 concentrations and the reconstruction of industrial CO_2 emissions are negligible; indeed, these are two of the better-known components of the global carbon cycle, especially during the Mauna Loa period. Similarly, any error in modeling the net uptake of CO_2 by the ocean that might account for the disagreement between simulation and observation must exceed the uncertainty represented by differences among the three carbon cycle models we use because all three models fail to produce the desired agreement; we assume that error

greater than this uncertainty is improbable and also negligible. Consequently, it remains that either the reconstructions of past land-use CO_2 release are in error or that there have been substantial historical exchanges between the atmosphere and those portions of the terrestrial biosphere not altered from preindustrial states by changes in land use.

In addition to the scientific interest in understanding the global biogeochemistry of carbon, resolution of the disagreement between simulation and observation of past changes in atmospheric CO_2 is important to the projection of future changes. First, if differences between observations and simulations were naively ignored and the simulations extended with assumptions about future anthropogenic emissions, the initial trajectories of the projections would be biased by 9–54 μL L^{-1}, depending on the choice of model and history of CO_2 release from changes in land use (Figure 5). Similarly, the projections' initial rates of change, influenced by input from the recent past, would be slightly larger than the observed rate of change. These initial biases would influence projected concentrations, especially in the near future. Furthermore, conventional projections of CO_2 concentrations assume that the global carbon cycle will continue to operate in the future as it has in the past. Consequently, confidence in projections is proportional to the understanding of past changes. If some carbon cycle dynamic of the past has been overlooked, as the noncoincidence of simulation and observation in Figure 5 suggests is possible, confidence in the future behavior of the carbon cycle is compromised. Failure to correctly project that dynamic into the future could result in erroneous projections of future changes in atmospheric CO_2. In short, improved coincidence between simulations and observations of past changes in atmospheric CO_2 is needed for projection of future changes.

Reconstruction of Past Terrestrial Biospheric Exchange by Deconvolution

As noted in the introduction to this paper, an estimate of past exchanges between the atmosphere and terrestrial biosphere can be obtained by constraining the ocean-atmosphere carbon model to reproduce the combined Siple–Mauna Loa record of atmospheric CO_2 and calculating the residual flux needed to achieve that fit [*Siegenthaler and*

Oeschger, 1987; *Keeling et al.*, 1989]. Again, interpretation of the residual flux as terrestrial biospheric exchange with the atmosphere is confounded by uncertainties in the deconvolution, but the estimates that result are extremely useful as alternatives for comparison with the direct historical-ecological reconstructions. Furthermore, they provide the additional benefit of allowing for the projection of future CO_2 changes from current concentrations and rates of change since they are produced by simulations that are constrained to reproduce these observations. Given the incompatibility of existing historical-ecological reconstructions of past land-use CO_2 release with conventional globally averaged one-dimensional models of ocean-atmosphere CO_2 exchange (Figure 5) [*Enting and Pearman*, 1986; *Enting and Mansbridge*, 1987] and with at least the first generation of regionalized two-dimensional tracer-based models [*Peng*, 1986; *Enting and Mansbridge*, 1987] and three-dimensional ocean general circulation models [*Keeling et al.* 1989], the constrained atmosphere approach to simulating past CO_2 changes is virtually indispensable for the projection of future changes.

In Figure 6 we compare our constrained simulation with the historical record of past changes in atmospheric CO_2. We used a modification of the approach to constrained atmosphere simulation used by *Killough and Emanuel* [1981], and we smoothed the simulation by cubic splines to just maintain a monotonic increase in simulated CO_2 concentration. Note that the simulated history of CO_2 is the same for each of the three models but that the residual flux required to achieve that simulation varies inversely with the oceanic uptake of the models (Figure 7). For example, the box-diffusion model simulates the smallest net oceanic uptake and consequently generates the largest residual flux in producing the simulation of Figure 6.

If the anthropogenic CO_2 emissions driving the model simulations are limited to industrial sources, the residual flux can be interpreted as the net exchange of carbon between the atmosphere and the entire terrestrial biosphere (Figure 7a). If CO_2 release from land-use change is also included (e.g., the histories of Figure 3), the residual flux can be interpreted

as the net exchange between the atmosphere and those portions of the terrestrial biosphere that have not been disturbed by land-use change (Figures 7b–d). In these latter simulations, the size and timing of the residual flux reflect the input from land-use change; the larger the estimate of CO_2 release from land-use change during the Mauna Loa period, the larger (more negative) the compensatory residual flux uptake must be to achieve the same observed change in atmospheric CO_2. Note the reduction in the residual flux from Figure 7b to Figure 7d with the change in land-use CO_2 history from the high estimate of *Houghton et al.* [1983] (history A, Figure 3) to the low estimate of *Houghton* [1989] (history C, Figure 3).

Interpretation of the residual flux as exchange with the terrestrial biosphere suggests either that net releases from past changes in land use have been appreciably lower than those estimated by the land-use change models or that there has been a significant amount of carbon uptake and sequestering by terrestrial ecosystems not experiencing land-use change. Indeed, with no CO_2 input from land-use change, the results from the box-diffusion and discrete-diffusion simulations suggest that the terrestrial biosphere as a whole, including both altered and unaltered systems, has been a small-to-moderate net sink for atmospheric CO_2 since about 1950 (curves 1 and 2 of Figure 7a). These results agree with those of *Keeling et al.* [1989, Figure 46] for their box-diffusion model calibrated with preindustrial ^{14}C and their version of the three-dimensional ocean model of *Maier-Reimer and Hasselman* [1987]. Our results from the discrete-advection model also suggest a recent global net biospheric sink, albeit much smaller and of shorter duration (curve 1, Figure 7a). This result is comparable to those of the *Siegenthaler and Oeschger* [1987] and the *Keeling et al.* [1989] box-diffusion models calibrated with bomb ^{14}C.

Interpreting the negative residual flux values from the simulations that use only industrial CO_2 inputs as global net CO_2 uptake by terrestrial ecosystems implies that these systems have in recent years assimilated and sequestered enough CO_2 to account for any CO_2 from industrial sources in excess of the increase in atmospheric CO_2 and that taken

up by the ocean, as well as any additional CO_2 from changes in land use. Accordingly, the larger the estimate of CO_2 release from those portions of the terrestrial biosphere undergoing changes in land use and acting as a source of atmospheric CO_2, the larger the inferred uptake by the natural or unaltered portions of the terrestrial biosphere must be (Figures 7b–d) to achieve the same total net terrestrial biospheric exchange with the atmosphere (Figure 7a).

Interestingly, the estimates of terrestrial biospheric CO_2 uptake inferred from the residual flux results are comparable to the 2.0–3.4 Gt yr^{-1} carbon sink required by *Tans et al.* [1990] to match the latitudinal gradient of atmospheric CO_2 and balance the carbon budget, although they use an entirely different approach to modeling oceanic CO_2 uptake. Further analysis of the estimates of terrestrial biospheric flux and past behavior of the terrestrial biosphere (e.g., the capacity of unconverted ecosystems to sequester the required carbon and mechanisms explaining the apparent historical increase in that sequestering) is of considerable interest but beyond the scope and objectives of this paper and will be treated elsewhere (see *Houghton* [1986] and *Keeling et al.* [1989] for related discussion). For our present purpose we next turn to the implications of these past terrestrial biospheric fluxes for projection of future changes in atmospheric CO_2 with simulations that have been constrained to reproduce past changes.

Implications for Future Changes

We begin by noting that future changes in atmospheric CO_2 tend to be dominated by the projected scenarios of change in industrial CO_2 emissions and uncertainty in what those emissions will be. Consequently we limit ourselves to a single scenario of future industrial CO_2 emissions, one that approximates a continuation of current trends in the use of fossil fuels (Table 1), and consider the influence of alternative scenarios of future terrestrial biospheric CO_2 exchange on projections of atmospheric CO_2 concentrations that use that scenario for future industrial CO_2 emissions.

Figure 8 shows projected CO_2 concentrations if we assume no net exchange between the atmosphere and terrestrial biosphere with future increases driven only by industrial CO_2 emissions. Despite identical constrained simulation of past changes (Figure 6), the model simulations slowly diverge as the simulations are continued into the next century. As before, the box-diffusion model yields the highest concentrations and the discrete-advection model the lowest, with a difference in 2100 of 53 μL L^{-1}. Again, for comparison, the observed change over the Mauna Loa period is approximately 35 μL L^{-1}. Thus differences in projected atmospheric CO_2 attributable to differences in the carbon cycle models (i.e., their representation of ocean structure and carbon transport) are not trivial. However, as we show in the following discussion, differences attributable to uncertainty in terrestrial biospheric exchange can exceed the differences among models.

Based on our deconvolutions of the Siple–Mauna Loa record, recent net carbon uptake by those portions of the terrestrial biosphere not disturbed by land-use change could be quite small, nearly zero, or as large as 3 Gt C yr^{-1} (Figure 7b–d). Assuming no net future terrestrial biospheric CO_2 release from land-use change or other sources, we can draw an envelope of uncertainty around the projected response to industrial CO_2 emissions that is a consequence of the uncertainty in past terrestrial biospheric exchange and the projection of that exchange into the future. One of many such possible envelopes is shown in Figure 9, with the upper bound formed by the discrete-diffusion model and zero future net biospheric exchange and the lower bound by the same model and a constant 3 Gt yr^{-1} carbon uptake by the terrestrial biosphere. Projection of smaller terrestrial biospheric uptake would of course narrow this envelope, elevating the lower bound. On the other hand, projection of a future biospheric uptake that increased with time, as the deconvolutions suggest may have occurred in the past, perhaps in response to changing climate or atmospheric CO_2, would expand the uncertainty envelope, depressing the lower bound.

Future changes in atmospheric CO_2 will of course be influenced by any significant release of CO_2 from future changes in land use. Projections of land-use CO_2 release are

scarce and uncertain. However, we can get some idea of their influence on projected changes in atmospheric CO_2 by using projections of future land-use CO_2 release provided by R. A. Houghton (personal communication, 1988) (Figure 10) (see [*Houghton*, 1990] for related projections). In Figure 11 we show the resulting envelope of uncertainty for the discrete-diffusion model, assuming zero net exchange with terrestrial ecosystems not disturbed by land-use change. The upper bound is produced when the population-based scenario of Figure 10 is used; the lower bound results from the reforestation scenario of Figure 10.

We want to emphasize that the uncertainty in projected CO_2 concentration resulting from uncertainty in past terrestrial biospheric CO_2 exchange (Figure 9) is of the same magnitude as that resulting from uncertainty in future land-use CO_2 release (Figure 11). Both exceed the uncertainty in ocean-atmosphere modeling (Figure 8) by about 50%. The combined uncertainty of ocean-atmosphere carbon cycle modeling and past and future terrestrial biospheric exchange is illustrated in Figure 12. The upper bound is from the box-diffusion model, assuming no future net CO_2 exchange with the unaltered terrestrial ecosystems and the population-based projection of future land-use CO_2 release. The lower bound is from the discrete-advection model assuming a constant 3 Gt yr^{-1} carbon uptake by unaltered terrestrial ecosystems and the reforestation scenario of future land-use change. A comparison of Figures 11 and 15 indicates that uncertainty about terrestrial biospheric exchange with the atmosphere increases the range of projected CO_2 concentrations for 2100 from 774–827 μL L^{-1} to 658–935 μL L^{-1}. Furthermore, the period in which a doubling of atmospheric CO_2 over preindustrial concentrations is achieved (i.e., a future concentration of approximately 555 μL L^{-1}) increases from 2056–2062 to 2041–2080.

CONCLUSIONS

Our results reaffirm earlier conclusions that the *Houghton et al.* [1983] population-based history of CO_2 release from past changes in land use, reconstructed by explicit consideration of carbon dynamics in terrestrial ecosystems disturbed by historical changes in

land use, is incompatible with measurements of atmospheric CO_2 and conventional ocean-atmosphere carbon cycle models [*Peng et al.*, 1983; *Enting and Pearman*, 1986; *Enting and Mansbridge*, 1987; *Keeling et al.*, 1989; *DOE Multi-Laboratory Climate Change Committee*, 1990] (see *Broecker et al.* [1980], *Oeschger and Heimann* [1983], *Elliot et al.* [1985], and *Enting and Pearman* [1986] for related discussions). We have also shown that more-recent estimates of the history of land-use CO_2 release based on the same approach do not significantly resolve the incompatibility.

An understanding of past terrestrial biospheric behavior is important for projecting future changes in atmospheric CO_2. Disagreement between simulations and the historical record of atmospheric CO_2 can lead to initial bias in the projection of future changes. Moreover, the residual carbon flux needed to balance observation, model, and history of CO_2 input to the atmosphere suggests unknown carbon cycle dynamics that can have appreciable impact on the projection of future changes in atmospheric CO_2. Our results show that uncertainty surrounding the past source-sink behavior of the terrestrial biosphere can have as much influence on the projection of future atmospheric CO_2 as uncertainty in future anthropogenic emissions.

The long-standing issue of the terrestrial biosphere's role as a historical source or sink for atmospheric CO_2 [e.g., *Reiners*, 1973; *Broecker et al.*, 1980; *Hobbie et al.*, 1984] has yet to be resolved. *Broecker et al.* [1980] concluded that understanding of global terrestrial biospheric dynamics was such that it was not possible to say whether the terrestrial biosphere of recent decades has been a source or sink for atmospheric CO_2, and consequently knowledge of the terrestrial biosphere could not be used to distinguish between alternative models of oceanic carbon uptake. A decade later, one can still reach that same conclusion.

There is need for continued efforts to reconstruct the role of the terrestrial biosphere in past changes in atmospheric CO_2 and to resolve incompatibilities between the deconvolution and historical-ecological approaches. The dilemma of relying on ocean models with uncertain ocean-atmosphere exchange that cannot be resolved by terrestrial biospheric

data to define the uncertain behavior of the terrestrial biosphere by deconvolution may be with us for some time, but progress can be made in the direct and explicit reconstruction of historical CO_2 exchange between atmosphere and terrestrial biosphere based on knowledge of terrestrial ecosystems. These efforts must continue to consider the history of land-use change and the associated carbon dynamics of disturbed ecosystems [sensu *Moore et al.*, 1981; *Houghton et al.*, 1983]. The improved correspondence between observations and simulations using land-use CO_2 release history C (Figure 5) with its assumptions of low tropical biomass suggests that careful attention should be given to estimating the biomass of tropical forests before and after land-use change [e.g., *Brown et al.*, 1989]. Simultaneously, there must be further consideration of the history of carbon dynamics in ecosystems that have not been substantially altered from preindustrial states by land-use change (e.g., high latitude boreal forests). From the general perspective of global biomass burning, improved estimates of fuelwood consumption, the use and impact of fire as an agent of land-use change, and the occurrence and impact of fire in natural ecosystems will all contribute to this effort.

Additional consideration should be given to the terrestrial biospheric dynamics of ^{13}C, including the influence of land-use disturbance. *Keeling et al.* [1989] have demonstrated how analysis of changes in atmospheric ^{13}C can aid in determining the terrestrial biosphere's contribution to changes in atmospheric CO_2 concentrations. Incorporation of ^{13}C into historical-ecological models of land-use change and carbon dynamics should prove useful in this analysis.

Finally, for ecosystems unaltered from preindustrial states as well those disturbed by changes in land use, additional consideration must be given to the past response of terrestrial carbon dynamics to rising concentrations of atmospheric CO_2 and other changes in the environment. Representations of terrestrial biospheric response to elevated CO_2 and its impact on atmospheric concentrations in global carbon cycle models that have attempted to model this dynamic [e.g., *Bacastow and Keeling*, 1973; *Oeschger et al.*, 1975; *Björkström*,

1979; *Goudriaan and Ketner*, 1984; *Kohlmaier et al.*, 1981, 1987; *Esser*, 1987] are often discounted for the lack of attention to physiological processes, ecological limitations, and the simple extrapolation of growth chamber results to the field and to global scales [e.g., *Goudriaan and Ajtay*, 1979; *Strain and Armentano*, 1982; *Dahlman*, 1985; *Peterson and Melillo*, 1985]. If these representations are indeed too simplistic, for example many do not include both climate and CO_2 response (but see *Esser* [1987]), the appropriate level of ecological realism should be determined and incorporated into global carbon cycle models that simulate historical changes in atmospheric CO_2 and tested against observed changes in ^{13}C and ^{14}C [*Bolin*, 1986].

Efforts to define current rates of tropical deforestation and the accompanying release of CO_2 should continue [e.g., *Houghton et al., 1985, 1987*; *Detwiler and Hall*, 1988]. But it is equally important to resolve the terrestrial biospheric exchange of the past several decades (both release and uptake). Indeed the presence or absence of a peak or maximum in the input of CO_2 to the atmosphere from the terrestrial biosphere prior to the Mauna Loa observation period may be crucial to the coincidence of simulated and observed atmospheric CO_2 [*Oeschger and Heimann*, 1983; *Enting and Mansbridge*, 1987; *Keeling et al.*, 1989]. Many of the model deconvolutions of past terrestrial biospheric behavior point to the existence of such a maximum [*Peng et al.*, 1983; *Emanuel et al., 1984*; *Stuiver et al.*, 1984; *Peng and Freyer*, 1986; *Siegenthaler and Oeschger*, 1987; *Keeling et al.*, 1989; Figure 7a, this paper]. (*Stuiver et al.*'s [1984] deconvolution of the $\delta^{13}C$ record of Pacific coastal trees is an exception.) With the exception of the *Houghton et al.* [1983] analysis based on Food and Agriculture Organization (FAO) statistics on land use and an exercise assuming larger carbon stocks in forests cleared prior to 1900 [*Houghton*, 1986], this peak is absent from historical-ecological reconstructions. Resolution of this and other historical behaviors of the terrestrial biosphere will go a long way towards improving our confidence in past and future behavior of the terrestrial biosphere and its role in the global carbon cycle. In this

way, knowledge of the terrestrial biosphere can better be used in the evaluation of ocean models, and our ability to project future changes in atmospheric CO_2 will be enhanced.

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REFERENCES

Bacastow, R. B., and C. D. Keeling, Atmospheric carbon dioxide and radiocarbon in the natural carbon cycle: II. Changes from A.D. 1700 to 2070 as deduced from a geochemical model, in *Carbon and the Biosphere*, AEC Symposium Series 30, CONF-720510, edited by G. M. Woodwell and E. V. Pecan, pp. 86–134, U.S. Atomic Energy Commission, Washington, D.C., 1973.

Björkström, A., A model of CO_2 interaction between the atmosphere, oceans and land biota, in *The Global Carbon Cycle*, SCOPE 13, edited by B. Bolin, E. T. Degens, S. Kempe, and P. Ketner, pp. 403–457, John Wiley and Sons, Chichester, England, 1979.

Bogdonoff, P., R. P. Detwiler, and C. A. S. Hall, Land use change and carbon exchange in the tropics: III. Structure, basic equations, and sensitivity analysis of the model, *Environ. Manage.*, *9*, 345–354, 1985.

Bolin, B., How much CO_2 will remain in the atmosphere? The carbon cycle and projections for the future, in *The Greenhouse Effect, Climatic Change, and Ecosystems*, SCOPE 29, edited by B. Bolin, B. R. Döös, J. Jäger, and R. A. Warrick, pp. 93–155, John Wiley and Sons, Chichester, England, 1986.

Broecker, W. S., T.-H. Peng, and R. Engh, Modelling the carbon system, *Radiocarbon*, *22*, 565–598, 1980.

Broecker, W. S., T.-H. Peng, G. Ostlund, and M. Stuiver, The distribution of bomb radiocarbon in the ocean, *J. Geophys. Res.*, *90*, 6953–6970, 1985.

Brown, S., A. J. R. Gillespie, and A. E. Lugo, Biomass estimation methods for tropical forests with applications to forest inventory data, *Forest Science*, *35*, 881–902.

Dahlman, R. C., Modeling needs for predicting responses to CO_2 enrichment: Plants, communities, and ecosystems, *Ecol. Modell.*, *29*, 77–106, 1985.

Detwiler, R. P., and C. A. S. Hall, Tropical forests and the global carbon cycle, *Science*, *239*, 42–47, 1988.

Detwiler, R. P., C. A. S. Hall, and P. Bogdonoff, Land use change and carbon exchange in the tropics: II. Estimates for the entire region, *Environmental Management*, *9*, 335–344, 1985.

DOE Multi-Laboratory Climate Change Committee, *Energy and Climate Change, Report of the DOE Multi-Laboratory Climate Change Committee*, 160 pp., Lewis Publishers, Chelsea, Mich., 1990.

Elliott, W. P., L. Machta, and C. D. Keeling, An estimate of the biotic contribution to the atmospheric CO_2 increase based on direct measurements at Mauna Loa Observatory, *J. Geophys. Res.*, *90*, 3741–3746, 1985.

Emanuel, W. R., G. G. Killough, W. M. Post, and H. H. Shugart, Modeling terrestrial ecosystems in the global carbon cycle with shifts in carbon storage capacity by land-use change, *Ecology*, *65*, 970–983, 1984.

Enting, I. G., and J. V. Mansbridge, The incompatibility of ice-core CO_2 data with reconstructions of biotic CO_2 sources, *Tellus*, *39B*, 318–325, 1987.

Enting, I. G., and G. I. Pearman, The use of observations in calibrating and validating carbon cycle models, in *The Changing Carbon Cycle: A Global Analysis*, edited by J. R. Trabalka and D. E. Reichle, pp. 425–458, Springer-Verlag, New York, 1986.

Esser, G., Sensitivity of global carbon pools and fluxes to human and potential climatic impacts, *Tellus*, *39B*, 245–260, 1987.

Freyer, H. D., Interpretation of the Northern Hemispheric record of the $^{13}C/^{12}C$ trends of atmospheric CO_2 in tree rings, in *The Changing Carbon Cycle: A Global Analysis*, edited by J. R. Trabalka and D. E. Reichle, pp. 126–150, Springer-Verlag, New York, 1986.

Friedli, H., H. Lötscher, H. Oeschger, U. Siegenthaler, and B. Stauffer, Ice core record of the $^{13}C/^{12}C$ ratio of atmospheric CO_2 in the past two centuries, *Nature*, *324*, 237–238, 1986.

Gammon, R. H., W. D. Komhyr, and J. T. Peterson, The global atmospheric CO_2 distribution 1968–1983: Interpretation of the results of the NOAA/GMCC measurment program, in *The Changing Carbon Cycle: A Global Analysis*, edited by J. R. Trabalka and D. E. Reichle, pp. 1–1 , Springer-Verlag, New York, 1986.

Goudriaan, J., and G. L. Ajtay, The possible effects of increased CO_2 on photosynthesis, in *The Global Carbon Cycle*, SCOPE 13, edited by B. Bolin, E. T. Degens, S. Kempe, and P. Ketner, pp. 237–249, John Wiley and Sons, Chichester, England, 1979.

Goudriaan, J., and P. Ketner, A simulation study for the global carbon cycle, including man's impact on the biosphere, *Clim. Change*, *6*, 167–192, 1984.

Hall, C. A. S., R. P. Detwiler, P. Bogdonoff, and S. Underhill, Land use change and carbon exchange in the tropics: I. Detailed estimates for Costa Rica, Panama, Peru, and Bolivia, *Environ. Manage.*, *9*, 345–354, 1985.

Hobbie, J. E., J. J. Cole, J. L. Dungan, R. A. Houghton, and B. J. Peterson, The controversy on the role of the biota in the global CO_2 balance, *BioScience*, *34*, 492–498, 1984.

Houghton, R. A., Estimating changes in the carbon content of terrestrial ecosystems from historical data, in *The Changing Carbon Cycle: A Global Analysis*, edited by J. R. Trabalka and D. E. Reichle, pp. 175–193, Springer-Verlag, New York, 1986.

Houghton, R. A., The long-term flux of carbon to the atmosphere from changes in land use, paper presented at the Third International Conference on Analysis and Evaluation of Atmospheric CO_2 Data Present and Past, World Meteorological Organization, Environmental Pollution Monitoring and Research Programme No. 59, Hinterzarten, Oct. 16–20, 1989.

Houghton, R. A., The global effects of tropical deforestation, *Envrion. Sci. Technol.*, *24*, 1990.

Houghton, R. A., and G. M. Woodwell, Global climatic change, *Sci. Am. 260*, 36–44, 1989.

Houghton, R. A., J. E. Hobbie, J. M. Melillo, B. Moore, B. J. Peterson, G. R. Shaver, and G. M. Woodwell, Changes in the carbon content of terrestrial biota and soils between 1860 and 1980: A net release of CO_2 to the atmosphere, *Ecol. Monogr.*, *53*, 235–262, 1983.

Houghton, R. A., R. D. Boone, J. M. Melillo, C. A. Palm, G. M. Woodwell, N. Meyers, B. Moore III, and D. L. Skole, Net flux of carbon dioxide from tropical forests in 1980, *Nature*, *316*, 617–620, 1985.

Houghton, R. A., R. D. Boone, J. R. Fruci, J. E. Hobbie, J. M. Melillo, C. A. Palm, B. J. Peterson, G. R. Shaver, G. M. Woodwell, B. Moore, D. L. Skole, and N. Meyers, The flux of carbon from terrestrial ecosystems to the atmosphere in 1980 due to changes in land use: Geographic distribution of the global flux. *Tellus*, *39B*, 122–139, 1987.

IPCC, Response Strategies Working Group of the Intergovernmental Panel on Climate Change, Draft report of the U.S.-Netherlands Expert Group on Emissions Scenarios, Bilthoven, The Netherlands, 1989.

Keeling, C. D., The carbon dioxide cycle: Reservoir models to depict the exchange of atmospheric carbon dioxide with the oceans and land plants, in *Chemistry of the Lower Atmosphere*, edited by S. I. Rasool, Plenum Press, New York, 1973a.

Keeling, C. D., Industrial production of carbon dioxide from fossil fuels and limestone, *Tellus*, *25*, 174–198, 1973b.

Keeling, C. D., Atmospheric CO_2 concentrations—Mauna Loa Observatory, Hawaii, 1958–1985, *NDP-001/R1*, Carbon Dioxide Information Center, Oak Ridge National Laboratory, Oak Ridge, Tenn., 1986.

Keeling, C. D., R. B. Bacastow, A. F. Carter, S. C. Piper, T. P. Whorf, M. Heimann, W. G. Mook, and H. Roeloffzen, A three-dimensional model of atmospheric CO_2 transport based on observed winds: 1. Analysis of observational data, in *Aspects of Climate Variability in the Pacific and the Western Americas*, Geophysical Monograph 55, edited by D. H. Peterson, pp. 165–236, American Geophysical Union, Washington D.C., 1989.

Killough, G. G., A dynamic model for estimating radiation dose to the world population from releases of ^{14}C to the atmosphere, *Health Phys.*, *38*, 269–300, 1980.

Killough, G. G., and W. R. Emanuel, A comparison of several models of carbon turnover in the ocean with respect to their distributions of transit time and age, and responses to atmospheric CO_2 and ^{14}C, *Tellus*, *33*, 274–290, 1981.

Kohlmaier, G. H., G. Kratz, H. Bröhl, and E. O. Sire, The source-sink function of the terrestrial biota within the global carbon cycle, in *Energy and Ecological Modelling*,

edited by W. J. Mitsch, R. W. Bosserman, and J. M. Klopatek, pp. 57–68, Elsevier Scientific Publishing Company, Amsterdam, 1981.

Kohlmaier, G. H., H. Bröhl, E. O. Siré, and M. Plöchl, Modelling stimulation of plants and ecosystem response to present levels of excess atmospheric CO_2, *Tellus*, *39B*, 155–170, 1987.

Maier-Reimer, E., and K. Hasselmann, Transport and storage in the ocean — An inorganic ocean-circulation carbon cycle model, *Clim. Dyn.*, *2*, 63–90, 1987.

Marland, G., and R. M. Rotty, Carbon dioxide emissions from fossil fuels: a procedure for estimation and results for 1950–1982, *Tellus*, *36B*, 232–261.

Marland, G., T. A. Boden, R. C. Griffin, S. F. Huang, P. Kanciruk, and T. R. Nelson, Estimates of CO_2 emissions from fossil fuel burning and cement manufacturing using the United Nations energy statistics and the U.S. Bureau of Mines cement manufacturing data, *ORNL/CDIAC-25*, *NDP-030*, 722 pp., Oak Ridge National Laboratory, Oak Ridge, Tenn., 1989.

Moore, B., R. D. Boone, J. E. Hobbie, R. A. Houghton, J. M. Melillo, B. J. Peterson, G. R. Shaver, C. J. Vörösmarty, and G. M. Woodwell, A simple model for analysis of the role of terrestrial ecosystems in the global carbon budget, in *Carbon Cycle Modelling*, SCOPE 16, edited by B. Bolin, pp. 365–385, John Wiley and Sons, New York, 1981.

Neftel, A., E. Moor, H. Oeschger, and B. Stauffer, Evidence from polar ice cores for the increase in atmospheric CO_2 in the past two centuries, *Nature*, *315*, 45–47, 1985.

Oeschger, H., and M. Heimann, Uncertainties of predictions of future atmospheric CO_2 concentrations, *J. Geophys. Res.*, *88*, 1258–1262, 1983.

Oeschger, H., U. Siegenthaler, U. Schotterer, and A. Gugelmann, A box diffusion model to study the carbon dioxide exchange in nature, *Tellus*, *27*, 168–192, 1975.

Peng, T.-H., Uptake of anthropogenic CO_2 by lateral transport models of the ocean based on the distribution of bomb-produced ^{14}C, *Radiocarbon*, *28*, 363–375, 1986.

Peng, T.-H., and H. D. Freyer, Revised estimates of atmospheric CO_2 variations based on the tree-ring ^{13}C record, in *The Changing Carbon Cycle: A Global Analysis*, edited by J. R. Trabalka and D. E. Reichle, pp. 151–159, Springer-Verlag, New York, 1986.

Peng, T.-H., W. S. Broecker, H. D. Freyer, and S. Trumbore, A deconvolution of the tree-ring based $\delta^{13}C$ record. *J. Geophys. Res.*, *88*, 3609–3620, 1983.

Peterson, B. J., and J. M. Melillo, The potential storage of carbon caused by eutrophication of the biosphere, *Tellus*, *37B*, 117–127, 1985.

Reiners, W. A., A summary of the world carbon cycle and recommendations for critical research, in *Carbon and the Biosphere*, AEC Symposium Series 30, CONF-720510, edited by G. M. Woodwell and E. V. Pecan, pp. 368–382, U.S. Atomic Energy Commission, Washington, D.C., 1973.

Revelle, R., and W. Munk, The carbon dioxide cycle and the biosphere, in *Energy and Climate*, National Research Council, Panel on Energy and Climate, R. Revelle, Chairman, pp. 140-158, National Academy of Sciences, Washington, D.C., 1977.

Richards, J. F., J. S. Olson, and R. M. Rotty, Development of a data base for carbon dioxide releases resulting from conversion of land to agricultural uses, *ORAU/IEA-82-10(M)*, ORNL/TM-8801, 140 pp., Oak Ridge National Laboratory, Oak Ridge, Tenn., 1983.

Siegenthaler, U., Uptake of excess CO_2 by an outcrop-diffusion model of the ocean, *J. Geophys. Res.*, *88*, 3599–3608, 1983.

Siegenthaler, U., and H. Oeschger, Biospheric CO_2 emissions during the past 200 years reconstructed by deconvolution of ice-core CO_2 data, *Tellus*, *39B*, 140–154, 1987.

Siegenthaler, U., M. Heimann, and H. Oeschger, Model responses of the atmospheric CO_2 level and $^{13}C/^{12}C$ ratio to biogenic input, in *Carbon Dioxide, Climate, and Society*, edited by J. Williams, pp. 79–87, Pergamon Press, Oxford, England, 1978.

Strain, B. R., and T. V. Armentano, Response of "unmanaged" ecosystems, Volume II, Part 12 of Environmental and societal consequences of a possible CO_2-induced climate change, *DOE/EV/10019-12*, 45 pp., U.S. Department of Energy, Washington, D.C., 1982.

Stuiver, M., P. D. Quay, and H. G. Ostlund, abyssal water carbon-14 distribution and the age of the world oceans, *Science*, *219*, 849–851, 1983.

Stuiver, M., R. L. Burk, and P. D. Quay, $^{13}C/^{12}C$ ratios in tree rings and the transfer of biospheric carbon to the atmosphere, *J. Geophys. Res.*, *89*, 11,731–11,748, 1984.

Sverdrup, H. U., M. W. Johnson, and R. H. Fleming, *The Oceans—Their Physics, Chemistry, and General Biology*, 1087 pp., Prentice-Hall, N.Y., 1942.

Takahashi, T., W. S. Broecker, A. E. Bainbridge, and R. F. Weiss, Carbonate chemistry of the Atlantic, Pacific, and Indian Ocean: The results of the GEOSECS expeditions, 1972–1978. *Technical Report No. 1, CV-1-80*, 15 pp., Lamont-Doherty Geological Observatory, Palisades, N.Y., 1980.

Tans, P. P., I. Y. Fung, and T. Takahashi, Observational constraints on the global atmospheric CO_2 budget, *Science*, *247*, 1431–1438, 1990.

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FIGURES

Fig. 1. Structural representation of the ocean in the three carbon cycle models. Arrows indicate the flow of carbon.

Fig. 2. The history of annual CO_2 release to the atmosphere from fossil fuels, flaring of natural gas, and cement manufacturing (—) [*Keeling*, 1973b; *Marland et al.*, 1989]. Fossil fuels contribute approximately 96.5% of the estimated annual industrial CO_2 emissions.

Fig. 3. Three histories of global net carbon release to the atmosphere from past changes in land use. History A is the population-based estimate of *Houghton et al.* [1983]. Histories B and C are from *Houghton* [1989]. High estimates of tropical biomass carbon are assumed in history B, and low estimates are assumed in history C. History B approximates the land-use CO_2 release history presented in *Houghton and Woodwell* [1989, p. 30, graph d].

Fig. 4. Comparison of model simulations (—) with the record of observed changes in atmospheric CO_2 from the Siple (◇) and Mauna Loa (○) records when the models' atmospheric CO_2 inputs are limited to the industrial source of Figure 2. Numbers refer to the models of Figure 1. The Siple record is the concentration of CO_2 in air bubbles trapped in old ice of an ice core extracted at Siple Station, Antarctica [*Neftel et al.*, 1985; *Friedli et al.*, 1986]; the Mauna Loa record is the annual average atmospheric CO_2 concentration recorded at Mauna Loa Observatory, Hawaii (○) [*Keeling*, 1986].

Fig. 5. Comparison of model simulations (—) with the combined Siple–Mauna Loa record of observed changes in atmospheric CO_2 (○) when the histories of past land-use CO_2 release from Figure 3 are combined with the industrial CO_2 emissions of Figure 2 as model input. (a) Simulations with history A (Figure 3). (b) Simulations with history B (Figure 3). (c) Simulations with history C (Figure 3). Observed concentrations are as in Figure 4.

Fig. 6. Simulation of past changes in atmospheric CO_2 (—) constrained to reproduce the observed changes of the combined Siple–Mauna Loa record (o). Observed concentrations are as in Figure 4.

Fig. 7. Residual flux required to produce the simulation of Figure 6 for different histories of land-use CO_2 release. Numbers refer to the models of Figure 1. (a) No land-use CO_2 release. (b) Simulations with history A (Figure 3). (c) Simulations with history B (Figure 3). (d) Simulations with history C (Figure 3).

Fig. 8. Simulations of future changes in atmospheric CO_2, assuming the industrial CO_2 emission scenario of Table 1 and no net exchange of CO_2 between the atmosphere and terrestrial biosphere. Simulations of past changes in atmospheric CO_2 are identical to the simulation of Figure 6. The upper curve is from the box-diffusion model (model 1, Figure 1), the middle curve is from the discrete-diffusion model (model 2, Figure 1), and the bottom curve is from the discrete-advection model (model 3, Figure 1).

Fig. 9. Envelope of uncertainty surrounding the the discrete-diffusion model's simulation of future changes in atmospheric CO_2 in response to the industrial CO_2 emission scenario of Table 1 that results from uncertainty in past terrestrial biospheric CO_2 exchange with the atmosphere and the extrapolation of that exchange into the future. In these simulations we assume no future CO_2 input to the atmosphere from changes in land use. The upper bound of the envelope results from the assumption of zero future net CO_2 exchange with the terrestrial biosphere; the lower bound results from the assumption of a constant 3 Gt C yr^{-1} uptake of CO_2 by the terrestrial biosphere.

Fig. 10. Projections of CO_2 release to the atmosphere from future changes in land use (Richard A. Houghton, personal communication, 1988) from the *Houghton* [1980] implementation of the *Houghton et al.* [1983] model of land-use change and CO_2 release. In the exponential increase scenario, tropical deforestation was assumed to increase exponentially. In the population-based increase scenario, regional deforestation was assumed to increase at the same rate as the population growth of the same region. In the reforestation scenario, rates of deforestation were assumed to decrease to zero by 2025 with extensive reforestation through abandonment of areas of shifting cultivation, planted pastures of Latin America, and the establishment of tropical tree plantation.

Fig. 11. Envelope of uncertainty surrounding the the discrete-diffusion model's simulation of future changes in atmospheric CO_2 in response to the industrial CO_2 emission scenario of Table 1 that results from uncertainty in future CO_2 release from changes in land use. In these simulations we assume no future net CO_2 exchange with those portions of the terrestrial biosphere not altered by land-use change. The dashed curve (- - -) is the simulated response to the industrial CO_2 inputs alone, assuming no net CO_2 exchange with the terrestrial biosphere. The upper solid curve (—) is an upper bound produced when the population-based CO_2 release scenario of Figure 10 is used; the lower solid curve (—) is a lower bound produced when the reforestation scenario of Figure 10 is used.

Fig. 12. Envelope of uncertainty surrounding the the discrete-diffusion model's simulation of future changes in atmospheric CO_2 in response to the industrial CO_2 emission scenario of Table 1 that results from the combined uncertainties in ocean-atmosphere carbon cycle modeling, past CO_2 exchange with the terrestrial biosphere and the extrapolation of that exchange into the future, and future CO_2 release from land-use change. The dashed curve (- - -) is the discrete-diffusion model's response to the industrial CO_2 inputs alone, assuming no net CO_2 exchange with the terrestrial biosphere. The upper solid curve (—) is an upper bound produced with the box-diffusion model, assuming zero future net CO_2 exchange with the terrestrial biosphere not altered by land-use change and the population-based projection of future land-use CO_2 release from Figure 10. The lower solid curve (—) is a lower bound produced with the discrete-advection model asumming a constant 3 Gt C yr^{-1} uptake of atmospheric CO_2 by that part of the terrestrial biosphere not disturbed by land-use change and the reforestation scenario of future land-use CO_2 "release" from Figure 10.

TABLE 1. Projected Industrial CO_2 Emissions

Year	CO_2 Emission, 10^{12} kg C yr^{-1}
2000	6.7
2025	10.1
2050	13.8
2075	18.0
2100	22.0

Industrial sources include commercial energy production and cement manufacturing [IPCC, 1989].

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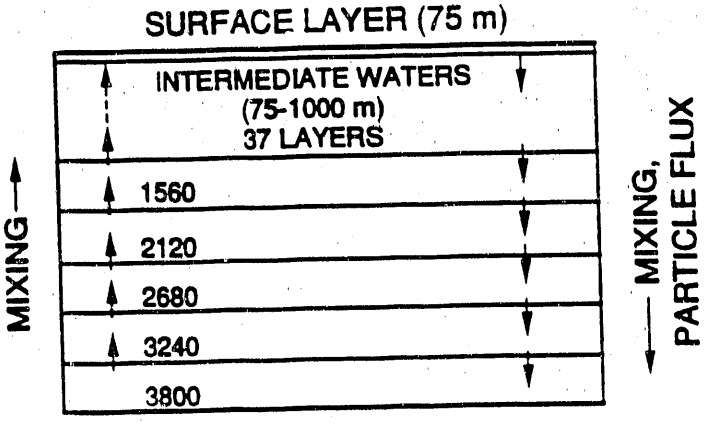
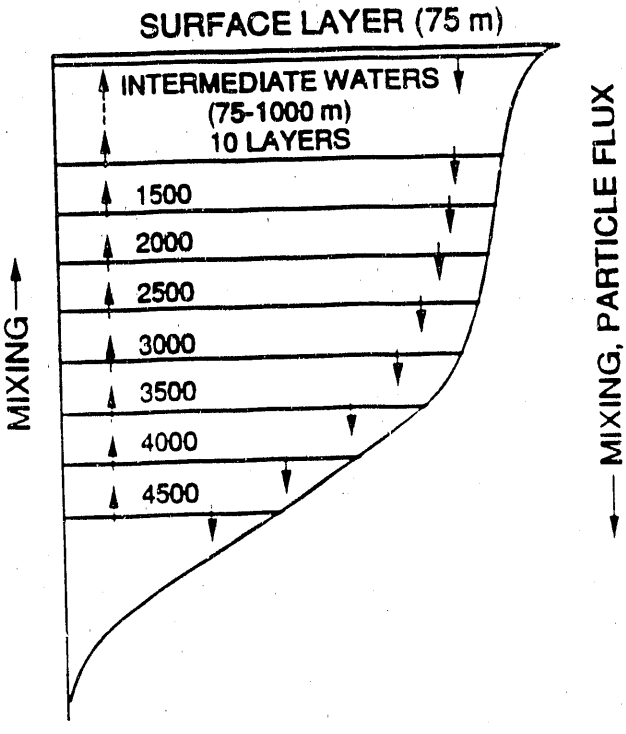
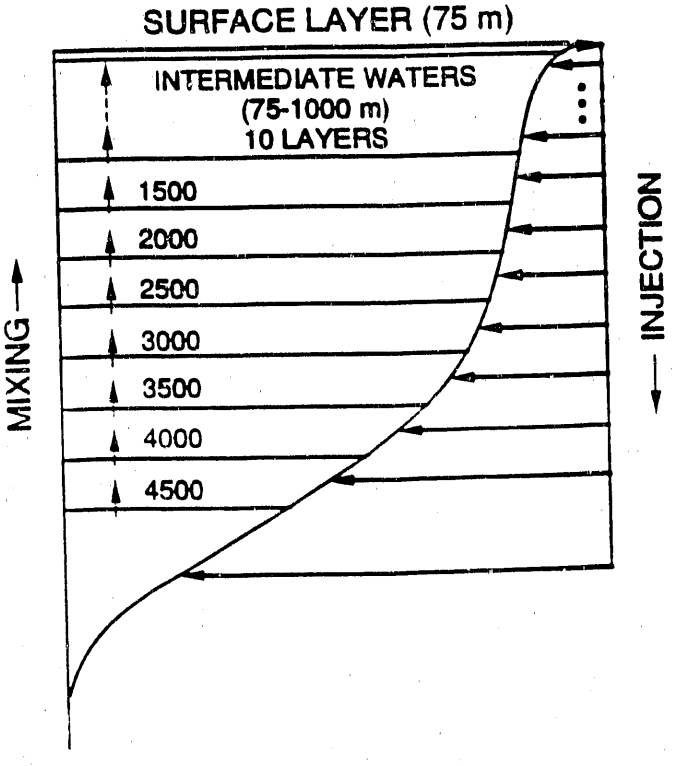


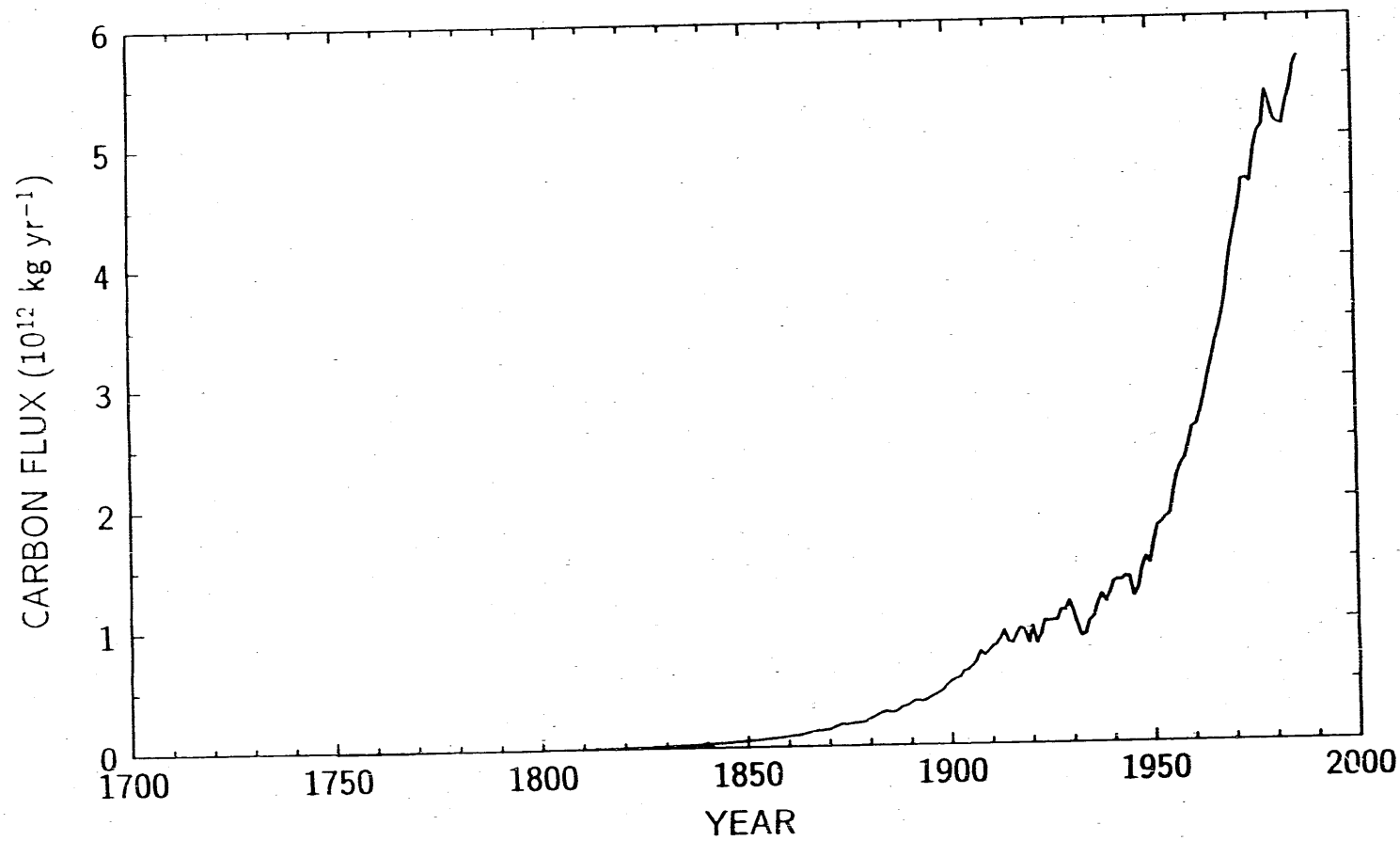
1 BOX-DIFFUSION MODEL

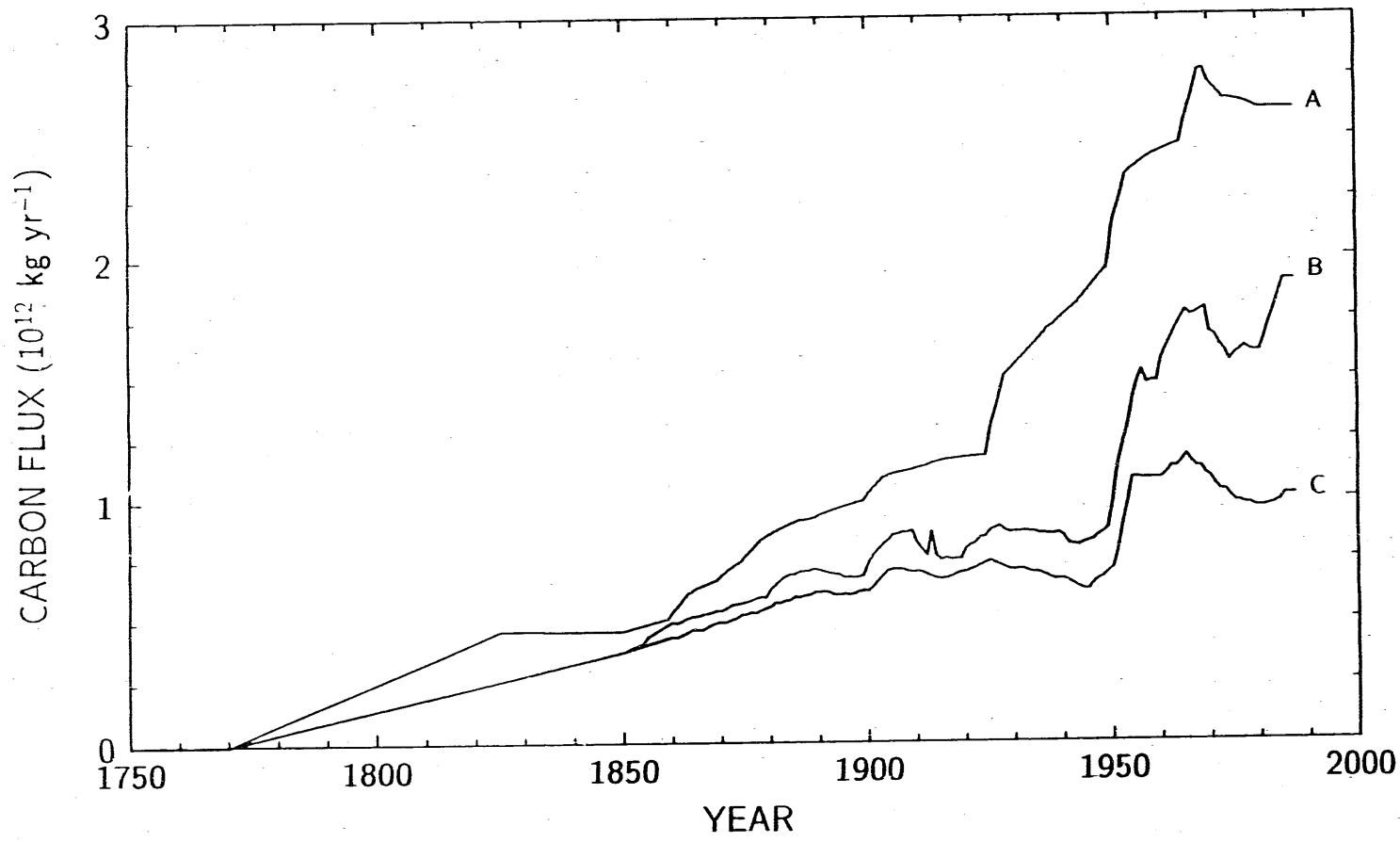


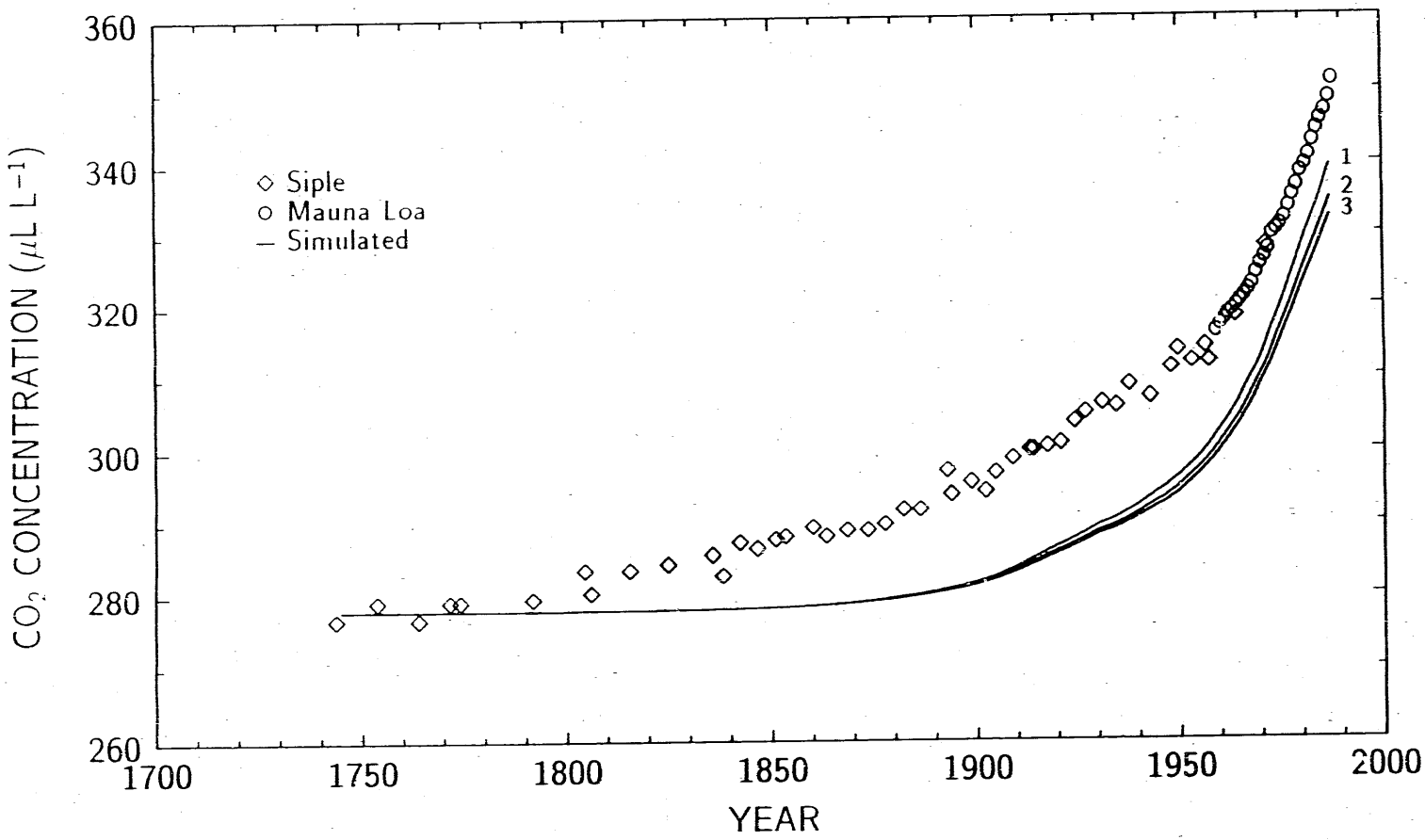
2 DISCRETE-DIFFUSION MODEL

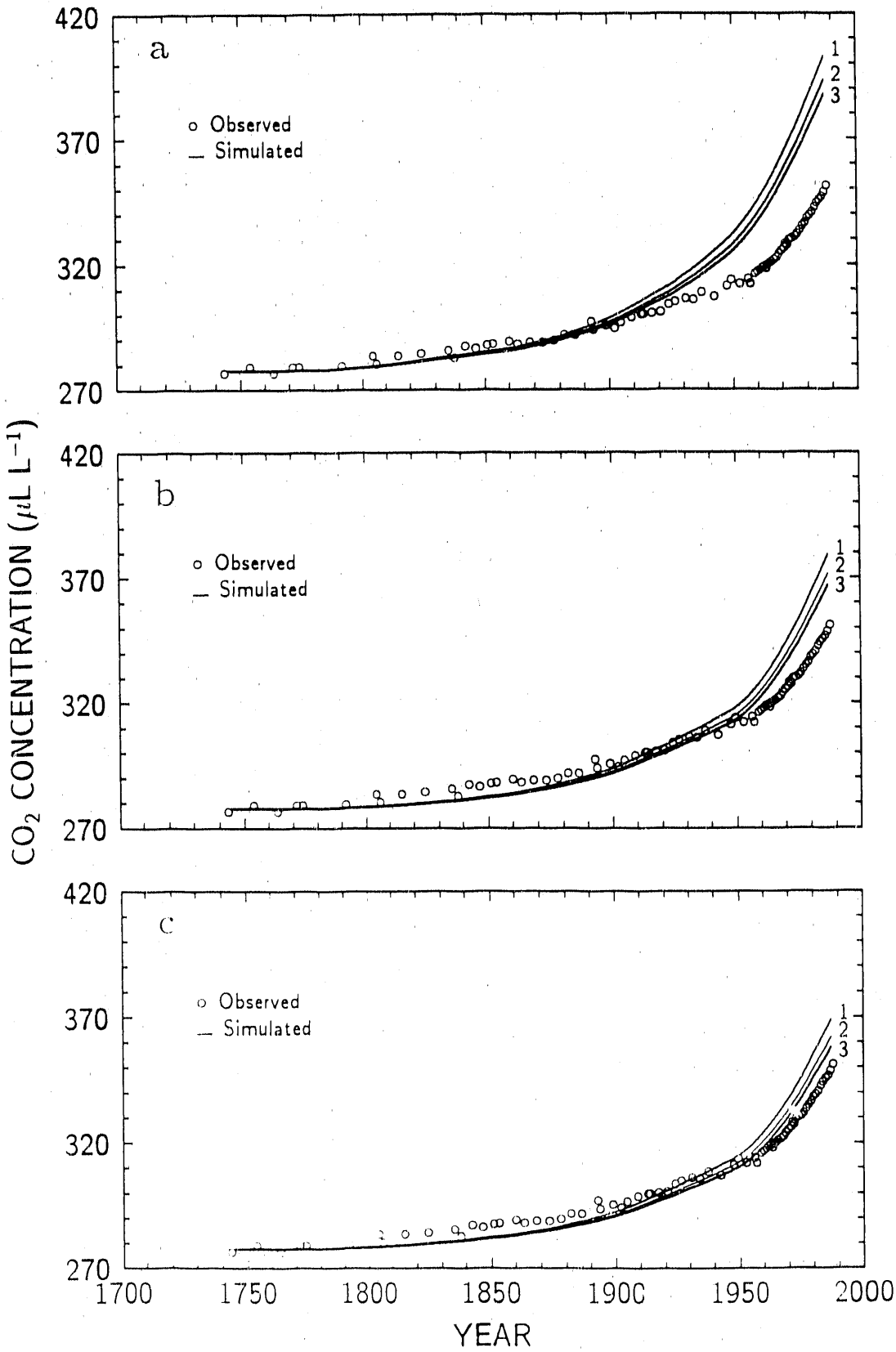


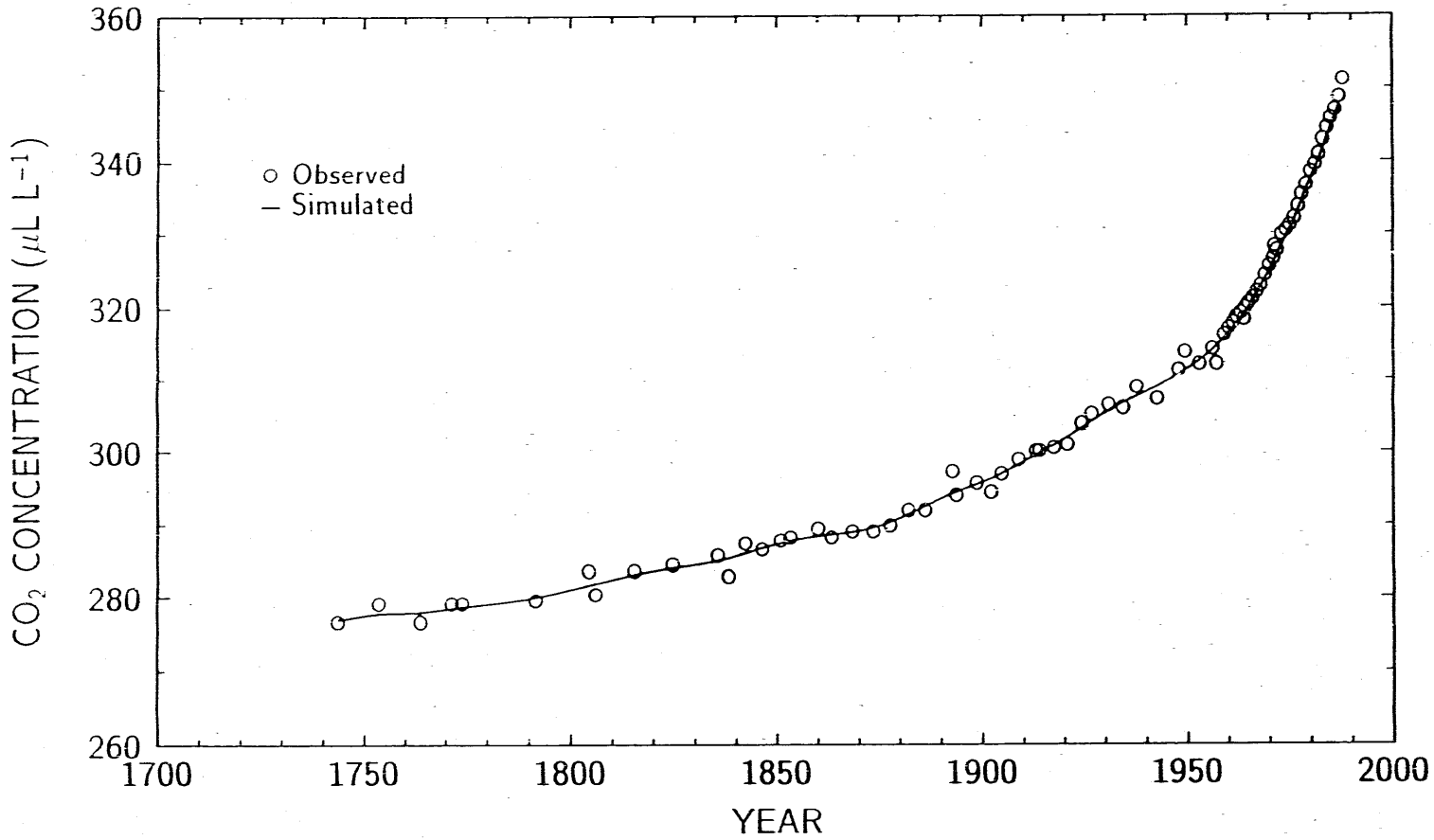
3 DISCRETE-ADVECTION MODEL

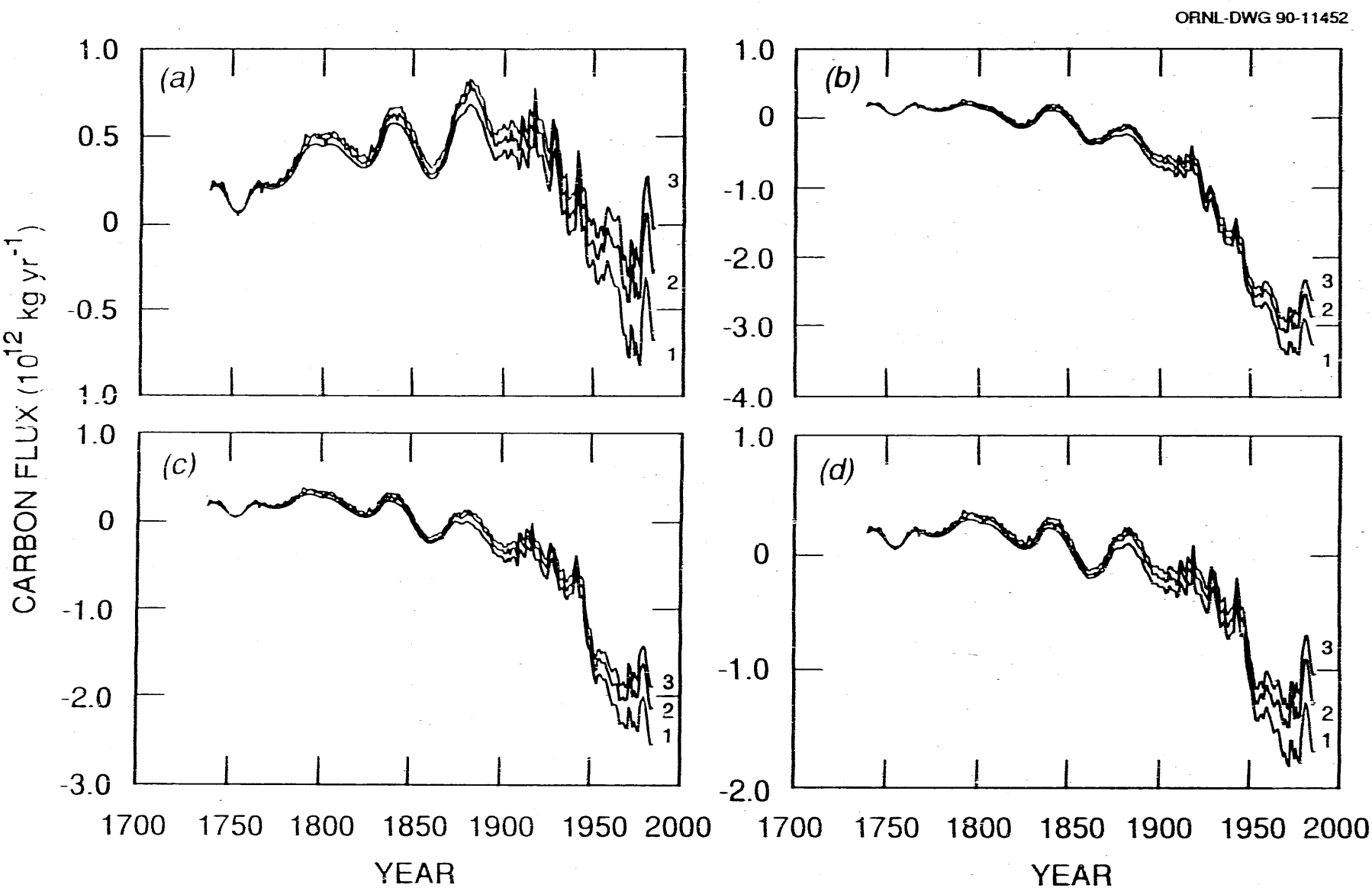

CARBON FLUX (10^{12} kg yr^{-1})
0
1
2
3
4
5
6
1700
1750
1800
1850
1900
1950
2000
YEAR

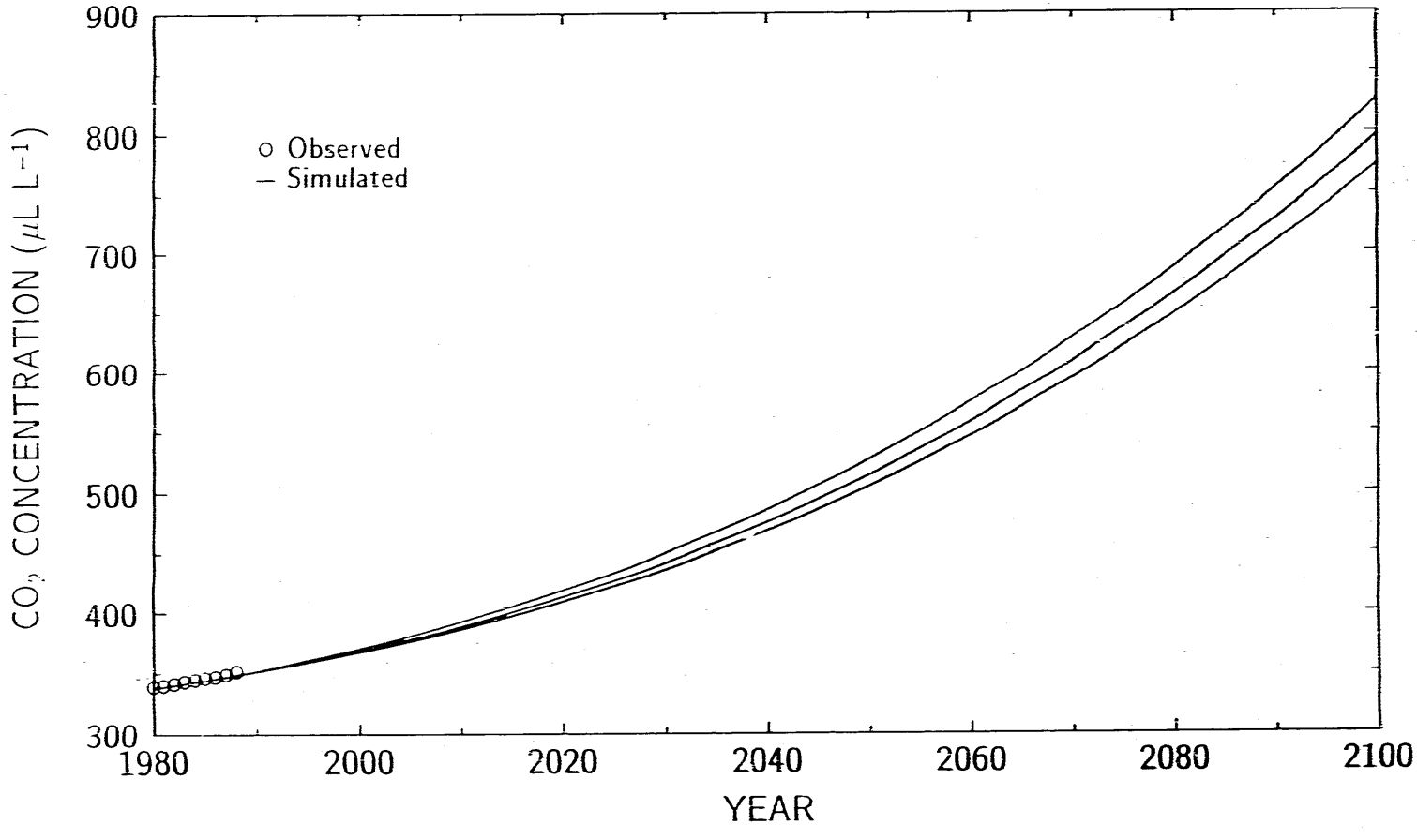

CARBON FLUX (10^{12} kg yr^{-1})
3
2
1
0
1750
1800
1850
1900
1950
2000
YEAR
A
B
C

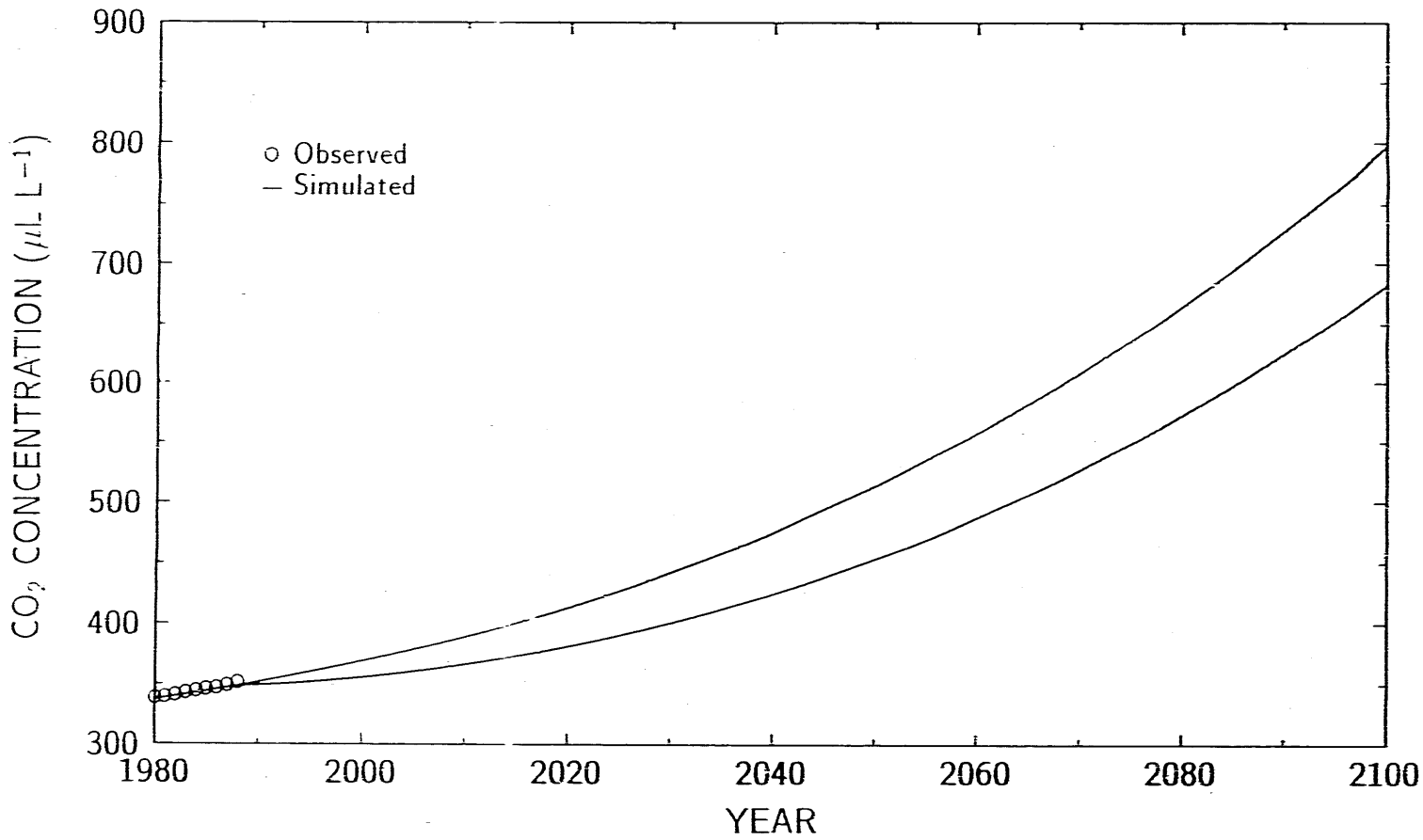

360
340
320
300
280
260
1700
1750
1800
1850
1900
1950
2000
YEAR
CO_2 CONCENTRATION (μL L^{-1})
◇ Siple
○ Mauna Loa
— Simulated
1
2
3

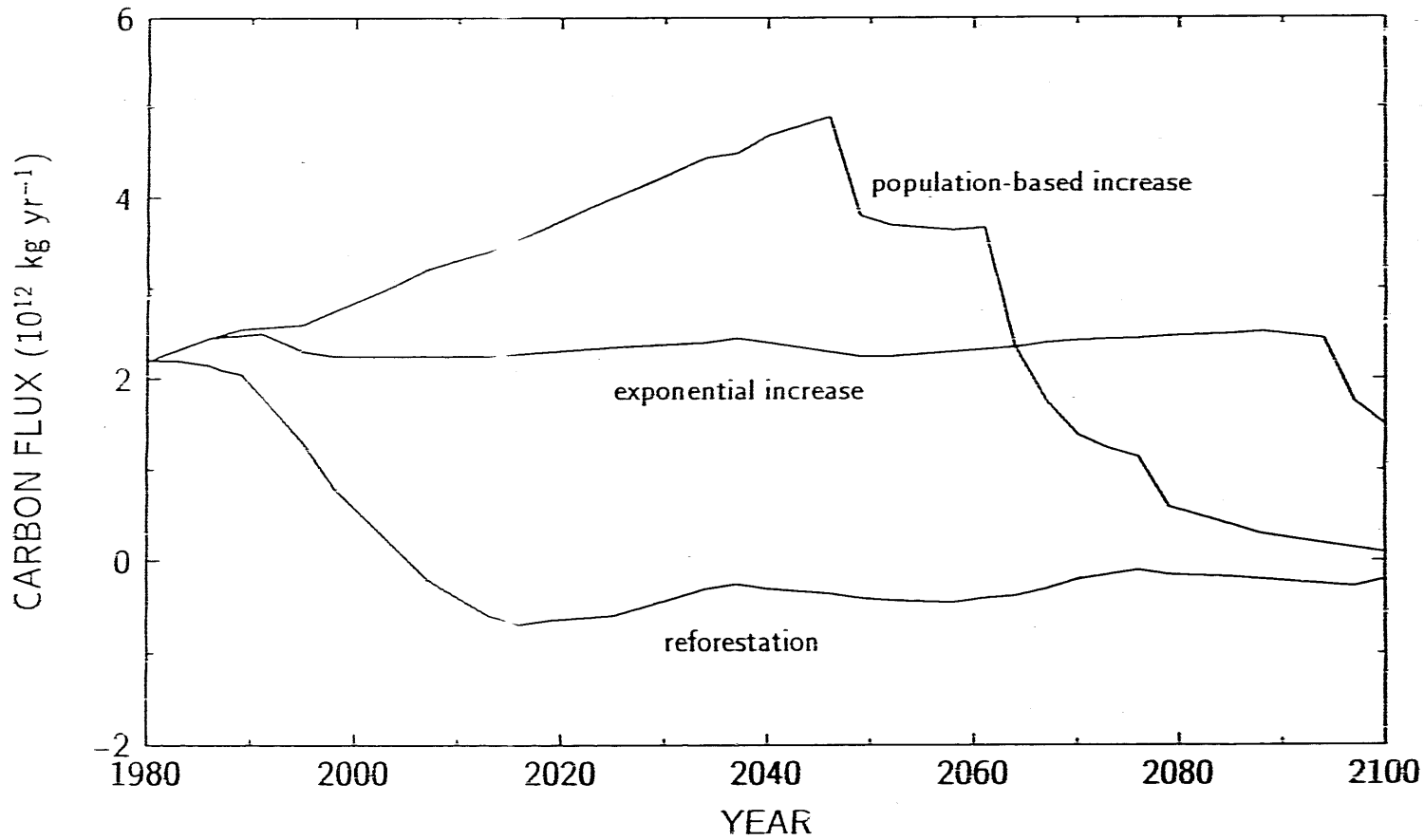

a
b
c
o Observed
— Simulated
1
2
3
420
370
320
270
CO2 CONCENTRATION (μL L−1)
1700
1750
1800
1850
1900
1950
2000
YEAR

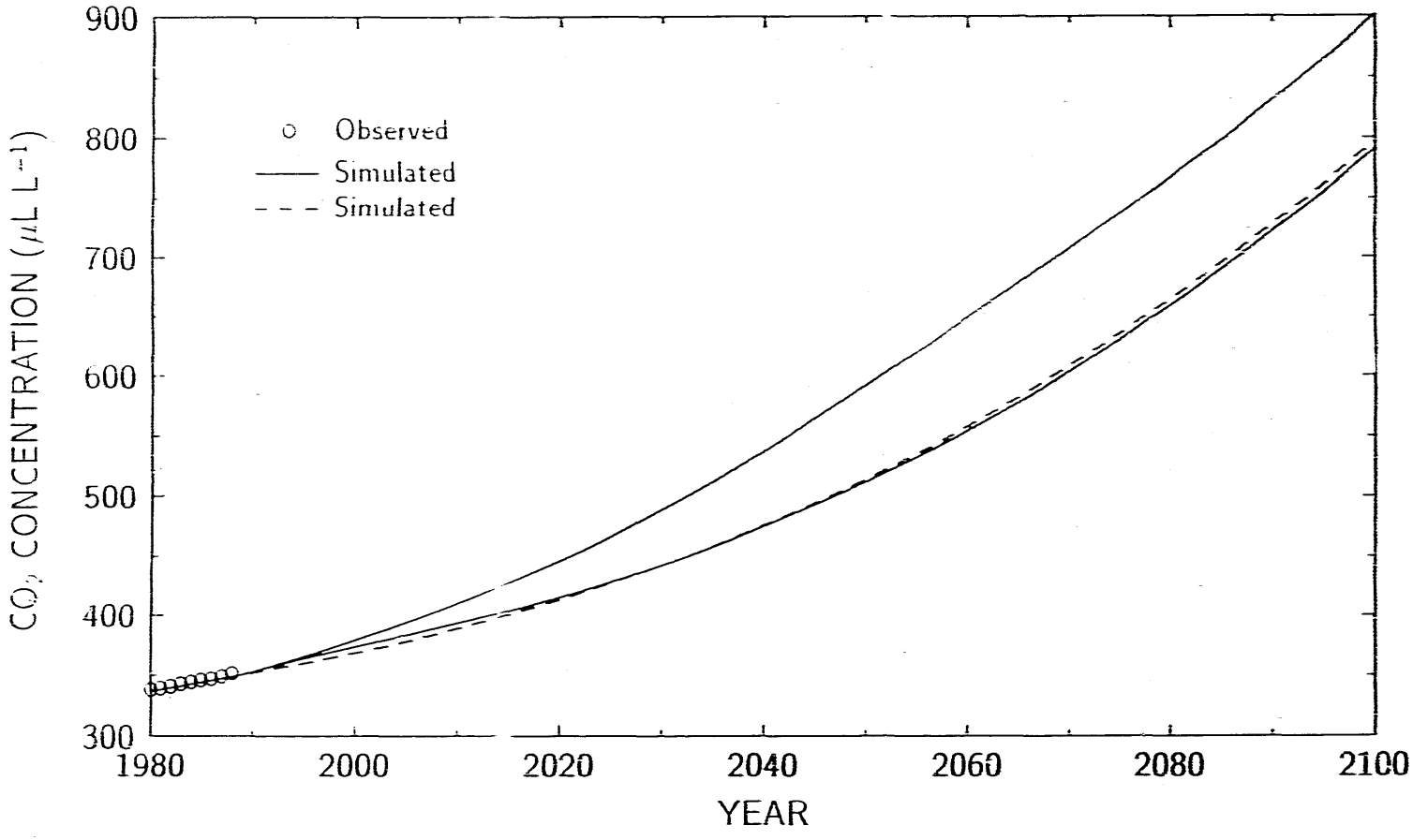

360
340
320
300
280
260
1700
1750
1800
1850
1900
1950
2000
YEAR
CO2 CONCENTRATION (μL L-1)
Observed
Simulated

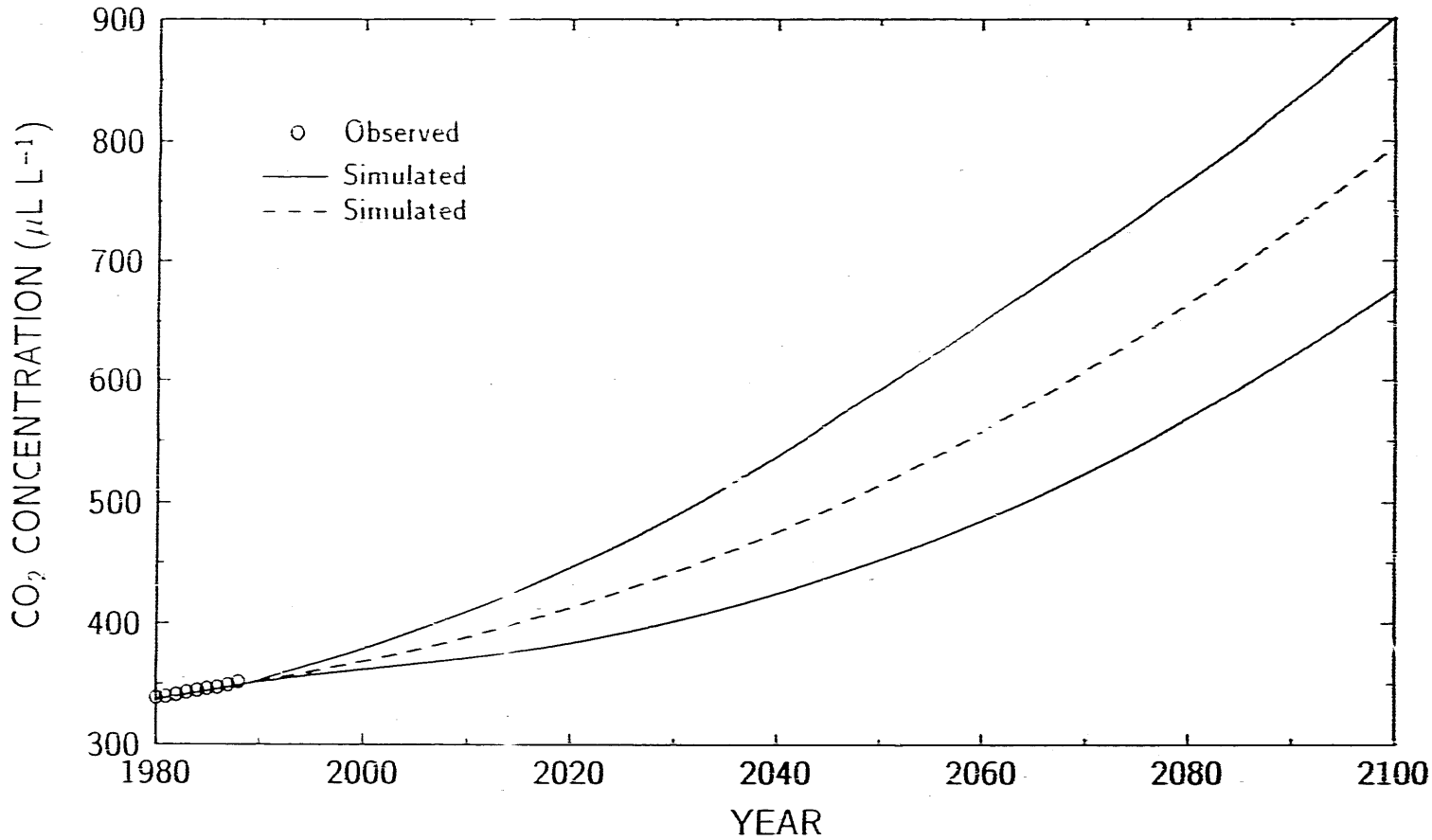

ORNL-DWG 90-11452
(a)
(b)
(c)
(d)
CARBON FLUX (10^{12} kg yr^{-1})
YEAR
YEAR
1700
1750
1800
1850
1900
1950
2000
1.0
0.5
0
-0.5
-1.0
-2.0
-3.0
-4.0
1
2
3


900
800
700
600
500
400
300
1980
2000
2020
2040
2060
2080
2100
YEAR
CO2 CONCENTRATION (μL L-1)
Observed
Simulated


900
800
700
600
500
400
300
1980
2000
2020
2040
2060
2080
2100
YEAR
CO2 CONCENTRATION (μL L-1)
Observed
Simulated


6
4
2
0
−2
1980
2000
2020
2040
2060
2080
2100
YEAR
CARBON FLUX (10^{12} kg yr^{-1})
population-based increase
exponential increase
reforestation


900
800
700
600
500
400
300
1980
2000
2020
2040
2060
2080
2100
YEAR
CO2 CONCENTRATION (μL L-1)
Observed
Simulated
Simulated


900
800
700
600
500
400
300
1980
2000
2020
2040
2060
2080
2100
YEAR
CO2 CONCENTRATION (μL L-1)
Observed
Simulated
Simulated

END

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