Formulating Energy Policies Related to Fossil Fuel Use: Critical Uncertainties in the Global Carbon Cycle.

W. M. Post, V. H. Dale, D. L. DeAngelis, L. K. Mann,
P. J. Mulholland, R. V. O'Neill, T. -H. Peng, M. P. Farrell

Environmental Sciences Division
Oak Ridge National Laboratory
Post Office Box 2008
Oak Ridge, Tennessee 37831

The global carbon cycle is the dynamic interaction among the earth's carbon sources and sinks. Understanding the global carbon cycle requires knowledge of the carbon exchanges between major carbon reservoirs by various chemical, physical, geological, and biological processes (Bolin et al., 1979; Rosenberg, 1981; and Solomon et al., 1985). Four reservoirs can be identified, including the atmosphere, terrestrial biosphere (usually including fresh water systems), oceans, and sediments (including fossil fuels). Atmospheric CO_2 concentration is determined by characteristics of carbon fluxes among major reservoirs of the global carbon cycle.

The objective of this paper is to document the knowns, unknowns and uncertainties associated with key questions that if answered will increase the understanding of the portion of past, present, and future atmospheric CO_2 attributable to fossil fuel burning. Documented atmospheric increases in CO_2 levels are thought to result primarily from fossil fuel use and, perhaps, deforestation. However, the observed atmospheric CO_2 increase is less than expected from current understanding of the global carbon cycle because of poorly understood interactions among the major carbon reservoirs.

Current Assumptions

The simplest method, (i.e., extrapolation) that could be used to estimate future atmospheric CO_2 levels requires the following assumptions:

- Currently measured trends can be extrapolated to produce accurate projections of future atmospheric CO_2 concentrations.
- The role of major processes affecting atmospheric CO_2 concentrations will not change in the future.

It is already known that these assumptions are untenable, and, as a result, carbon cycle descriptions based on them cannot be used to accurately predict future CO_2 concentrations. However, the assumptions have several useful purposes and point out the need for an approach that will define those aspects of the global carbon cycle necessary to predict future atmospheric levels of CO_2 with greater certainty.

DISCLAIMER

To resolve uncertainties associated with key carbon cycle processes, we have identified three questions that provide a framework within which assumptions can be tested and uncertainties reduced. These organizational questions are:

1. What are the ramifications of assuming that perturbation from fossil fuel burning dominates carbon cycle processes regulating atmospheric concentrations of CO_2?

2. Will the assumption that carbon cycle processes remain unaltered by future atmospheric CO_2 levels cause significant errors in atmospheric CO_2 projections?

3. What additional knowledge of carbon cycle processes is needed to accurately estimate future atmospheric CO_2 concentrations?

Answers to each of these questions will be needed to resolve global carbon cycle ambiguities. In the following sections of this paper, each of these questions are defined with a statement of the carbon cycle problem and the key knowns, unknowns and uncertainties that must be resolved. Each question is further divided into additional questions dealing with uncertainties in specific carbon pools and/or carbon fluxes.

What are the ramifications of assuming that perturbation from fossil fuel burning dominates carbon cycle processes regulating atmospheric CO_2 concentrations?

A fundamental assumption underlies research into the global carbon cycle: use of fossil fuels is primarily responsible for the recent increase in atmospheric CO_2, and continued fossil fuel use will contribute to further atmospheric CO_2 increases. Scientific consensus supports this assumption. However, if other factors are significant in controlling the increase of atmospheric CO_2 concentrations, then an emphasis on energy policies related to fossil fuel use may not be justified. The role of processes other than fossil fuel use in determining future atmospheric CO_2 levels needs to be defined.

Although supported by scientific consensus, continued emphasis should be placed on determining whether or not single processes other than fossil fuel emissions are controlling the recent increase in atmospheric CO_2. The largest global net fluxes of carbon in the period 1800 to present are releases from burning fossil fuel [150 to 190 Pg C (Rotty, 1987)], uptake by the ocean [27% to 41% of fossil fuel release or 40 to 78 Pg C (Peng and Broecker, 1984)], and the release of carbon due to land use [135 to 228 Pg C (Houghton et al., 1983)]. These estimates suggest that 207 to 378 Pg C were added to the atmosphere during that time period. However, the amount of carbon in the atmosphere increased by only 129 to 172 Pg C (Bolin, 1986). The two sets of values do not overlap. This discrepancy underscores the fact that current knowledge is insufficient to corroborate or negate the possibility that uncertainties of ocean and land-use dynamics are as

important as fossil fuel burning in explaining the observed increases in atmospheric CO_2 levels (Trabalka et al., 1985).

Will explicit treatment of more detailed ocean dynamics significantly alter estimates of the rate of CO_2 uptake from the atmosphere?

PROBLEM: Global ocean uptake of fossil fuel CO_2 is estimated from ocean-atmosphere models that simplify complex ocean dynamics. Uncertainties about the adequacy of treatment of oceans in existing models are responsible for a large portion of uncertainties in predicting both atmospheric CO_2 increases and climate responses over the next 100 to 200 years.

KNOWNS, UNKNOWNS, UNCERTAINTIES: Our current understanding of the exchanges between atmospheric and oceanic carbon has been developed from three sources: (1) analysis of ocean carbonate chemistry, (2) estimation of CO_2 exchange rates from radon and ^{14}C measurements, and (3) determination of mixing and circulation from measurements of the distribution of various tracers, especially bomb-^{14}C and tritium. Various models have synthesized data and theory concerning these three approaches to make quantitative estimates of the global exchange flux between the ocean and the atmosphere. Over 30 model experiments have been published. Estimates of the global atmosphere-ocean exchange flux range from 45 to 140 Pg Cyr^{-1}, although current consensus places the estimates in the range of 90 to 104 Pg Cyr^{-1}.

Ocean-atmosphere research proceeded on the assumption that a 0.5 to 1.5 Pg Cyr^{-1} net terrestrial sink of atmospheric CO_2 could explain discrepancies between atmospheric CO_2 changes and ocean uptake. As knowledge of terrestrial-atmosphere flux history improved, it became apparent that the terrestrial system has been a source of CO_2 as a result of land-use practices. Current release (1980) is now believed to be 0.9 to 2.9 Pg Cyr^{-1} (Houghton et al., 1985; Detwiler et al., 1985; and Melillo et al., 1988). Land-use releases of CO_2 of this magnitude are reconcilable with potential carbon cycle balances over short time periods. It remains impossible to account for the timing and cumulative land-use release from 1800 to 1980 [estimated at 135 to 228 Pg C (Houghton et al., 1983)]. This difficulty has led to the dilemma that as much as 35 to 249 Pg C more CO_2 has entered the atmosphere as CO_2 than can be accounted for on the basis of current atmospheric CO_2 levels and estimated exchange rates between the atmosphere and various sources and sinks of CO_2. It is conceivable, therefore, that the oceans may take up considerably more CO_2 than can be explained by current ocean models (Emanuel et al., 1984; Peng et al., 1983; and Peng and Freyer, 1986). However, refinements to current one-dimensional and two-dimensional ocean models to incorporate more processes (e.g., polar outcrop, biological activity, nutrient cycling, and upwelling) do not account for any more carbon uptake than did the simple box-diffusion models

(Emanuel et al., 1985a; and Killough and Emanuel, 1981). Further increases in confidence of the estimates of ocean-atmosphere carbon exchange will require three-dimensional representation of the water mass structure and dynamics of the ocean.

Is the CO_2 released from terrestrial land-use changes responsible for the recent atmospheric CO_2 increase?

PROBLEM: The net flux of carbon between terrestrial ecosystems and the atmosphere has been impossible to measure directly, and the many methods that have been used to estimate the flux indirectly provide contradictory estimates. Deconvolution methods using $^{13}C/^{12}C$ ratios in tree rings (Peng et al., 1983; Peng and Freyer, 1986; and Emanuel et al., 1984) and CO_2 measured in ice cores (Siegenthaler and Oeschger, 1987) have generally shown that the additional flux from land clearing can be no larger than 1 Pg Cyr^{-1} since 1958. In contrast, reconstruction analyses using historical data estimate annual net flux to the atmosphere from land use during 1958 to 1980 to range from 0.9 to 2.9 Pg Cyr^{-1}, and, for the entire period between 1800 to 1980, from 135 to 228 Pg C (Houghton et al., 1983). This flux is of the same size as the estimated fossil fuel release (150 to 190 Pg C) over the same time period. Estimates of this magnitude contribute to the problem that a possible 35 to 249 Pg C released from all sources since 1800 has not been taken up by oceans or appeared in the atmosphere.

KNOWNS, UNKNOWNS, UNCERTAINTIES: Deconvolution studies are sensitive to assumptions on how other parts of the system, particularly ocean carbon uptake, are behaving. This sensitivity affects the estimated pattern of carbon released through time. Sources of this uncertainty could include insufficient ocean model carbon uptake, inadequacies in the ice core CO_2 or tree ring ^{13}C records used, or inappropriate conceptualization of carbon cycle processes. The large uncertainties in reconstruction studies arise from at least four components of the analysis of historical terrestrial carbon flux:

1. Standing stocks of carbon in biomass in unmanaged ecosystems (Olson et al., 1983; and Brown and Lugo, 1984). The range of uncertainty for all vegetation is 311 to 727 Pg C globally.

2. Rates of land clearing and abandonment, particularly in the tropics (Detweiler et al., 1985; Molofsky et al., 1986; FAO, 1983; and Myers, 1980 and 1984). Estimates of current global land clearing range from 5.3 to $41.7 \cdot 10^6$ ha/yr.

3. Rate of biomass recovery after disturbance and abandonment from use [<1% to 20% per year (Pastor and Post, 1986; and Brown and Lugo, 1982)].

4. Degree of decrease of various carbon pools as the result of disturbance (Schlesinger, 1986; Mann, 1985, 1986) and of material losses (Seiler and Crutzen, 1980; Maybeck, 1981; and Schlesinger and Melack, 1981).

Are there other sources of potentially large fluxes?

The possibility cannot be excluded that other sources or sinks of atmospheric CO_2 may redefine the role of fossil fuel in increasing atmospheric CO_2. Currently, there are no candidate fluxes that merit the concern expressed for the uncertainties in ocean uptake and land-use release. Processes that may be determined to be important enough to account for the exchange of several petagrams of carbon with the atmosphere are discussed in the third research question. If any of these or yet other processes are proven to be significant to estimating atmospheric CO_2 concentrations, then their role in the global carbon cycle will need to be assessed..

Will the assumption that carbon cycle processes remain unaltered by higher atmospheric CO_2 levels in the future cause significant errors in atmospheric CO_2 projections?

For at least the last 100,000 years, a balance between positive and negative feedback processes may have been responsible for atmospheric CO_2 concentrations remaining in the relatively narrow range of 200 to 350 ppmv (Neftel et al., 1982; Broecker, 1982; McElroy, 1983; and Sundquist 1986). In the future, increasing atmospheric CO_2 levels may significantly reduce or eliminate some feedbacks, enhance existing feedbacks, or produce new feedbacks in the global carbon cycle. The consequent changes in atmospheric CO_2 concentrations could shift the carbon cycle to a new mode of operation (Sundquist, 1986; and Kasting and Ackerman, 1986). Thus, a qualitative shift could have dramatic quantitative repercussions. Projections of future CO_2 levels made without consideration of altered feedbacks and their potential for changing carbon cycle processes would be inaccurate. Climate changes or other processes capable of altering currently large carbon fluxes or the rates of release of CO_2 from large carbon pools could halve or double the current rate of atmospheric CO_2 increase.

Future CO_2-induced climate change is the most plausible (though not the only) source of global carbon cycle destabilization. Increasing atmospheric CO_2 is likely to produce chronic changes in global climate (MacCracken, 1985; and Luther, 1985), as it may have done in the geologic past (Oeschger and Stauffer, 1986). Future CO_2-induced

temperature and precipitation distribution changes could equal or exceed the changes which have occurred over the past 100,000 years and to which the natural carbon cycle has responded (Solomon and Tharp, 1985; Sundquist, 1985; and Olson et al., 1985).

Several important properties of the global carbon cycle may be greatly altered by future climate changes of the magnitude currently projected. For example, five processes that could involve large carbon fluxes (>2 Pg Cyr^{-1}) or large carbon pools (>200 Pg) and that could be modified by CO_2-induced climate changes are described below. Increases in atmospheric CO_2 concentrations could be amplified by changes in (a) ocean circulation, (b) the ocean biological pump, (c) terrestrial ecosystem respiration and production, (d) the terrestrial hydrological cycle, and (e) land uses. Additional processes may also be identified. The following text defines the potential of the above processes to destabilize atmospheric CO_2 concentrations and it outlines future research needs.

Will effects of climate changes on ocean circulation reduce future oceanic CO_2 uptake?

PROBLEM: Ocean circulation is a major factor controlling fluxes of CO_2 between the atmosphere and the ocean. Net oceanic uptake of CO_2 is approximately 1.5 to 3.3 Pg Cyr^{-1} (Trabalka et al., 1985), or nearly one half of the annual release of fossil fuel carbon. A 50% change in this flux would double or halve future atmospheric CO_2 concentrations over a few centuries. The future CO_2-induced temperature increase and the redistribution of atmospheric moisture over oceans could reduce the ocean as a net sink of atmospheric CO_2. This reduction could double the current rate of atmospheric increase of 3 to 6 Pg Cyr^{-1}. The change would involve shifting rates of deep water formation and patterns of global ocean circulation.

KNOWNS, UNKNOWNS, UNCERTAINTIES: Whether the oceans would release or store CO_2 in response to warming is not predictable. Large geographic and seasonal variability in surface ocean pCO_2 levels, and hence in potential CO_2 sources and sinks, have been recorded (Takahashi et al., 1985 and 1986). Climate (particularly temperature) affects ocean circulation by its influence on upwelling, mixing, advection, and intermediate and deep water formation. Indications from Greenland ice cores reveal a close relationship between climate oscillations and changes in the production rate of deep water in the North Atlantic Ocean. For example, the warming of the ocean-atmosphere system at the end of the last glacial period by 2°C was associated with an atmospheric CO_2 increase of about 80 ppmv (Broecker and Peng, 1986).

Will the effects of climate changes on ocean biological productivity reduce ocean CO_2 uptake?

PROBLEM: Biological productivity converts inorganic carbon into organic detritus that eventually sinks to the deep ocean. This process differs from uptake of inorganic carbon by chemical absorption and physical transportation to other parts of the ocean. The result is net removal of carbon from the surface layer, which permits an additional influx of CO_2 to the ocean surface waters. Ocean models by Sarmiento and Toggweiler (1984), Knox and McElroy (1984), and Siegenthaler and Wenk (1984) suggest that changes in biological productivity at high latitudes may have a strong influence on oceanic CO_2 uptake and, hence, on atmospheric CO_2 concentrations.

KNOWNS, UNKNOWNS, UNCERTAINTIES: The geographic distribution of marine productivity can influence oceanic source and sink properties. Of the 20 to 58 Pg Cyr^{-1} that have been estimated as net primary production (NPP) of the open ocean (DeVooys, 1979; Bolin et al., 1979; Dawes, 1981; and Chavez and Barber, 1987), the amount of marine particulate matter that sinks from the surface layer of the open ocean is estimated to be from 0.4 to about 22 Pg Cyr^{-1} (Eppley and Peterson, 1979; Broecker and Peng, 1982; Bolin et al., 1979; and Chavez and Barber, 1987). Net primary productivity in estuarine and coastal waters totals about 8 to 13 Pg Cyr^{-1} (Wollast and Billen, 1981; and Dawes 1981), and a relatively large fraction of this amount (1 to 5 Pg Cyr^{-1}) could be buried in coastal sediments. Decreases in nutrient supply and, hence, the decrease in biogenic carbon flux by as little as 5% (e.g., 0.02 to 0.25 Pg Cyr^{-1}) would increase the CO_2 content of the atmosphere by 8 ppmv. Support of this possibility is given by recent studies that show that the atmospheric CO_2 increase at the end of the last continental glaciation is correlated with decreases in marine photosynthesis at high latitudes (Sarmiento and Toggweiler, 1984; Knox and McElroy, 1984; and Siegenthaler and Wenk, 1984).

Will terrestrial ecosystems release or store carbon in response to changing climates?

PROBLEM: The terrestrial biota will certainly respond to changes in climate. Changed geographic distribution and extent of vegetation zones may reduce the amount of CO_2 sequestered in terrestrial ecosystems over long enough time periods for ecological succession to occur (decades to centuries). Over shorter time periods, ecosystem respiration and production rates will respond to climate change and will alter the amounts of CO_2 released by the terrestrial biota.

KNOWNS, UNKNOWNS, UNCERTAINTIES: About 560 Pg C is estimated to be stored in vegetation (Olson et al., 1983) and another 1400 Pg C in soils (Zinke et al., 1984). However, terrestrial carbon is not uniformly distributed. One-third of all above-ground carbon resides in north temperate regions between 45°N and 70°N latitude, and one-third is found between 10°N and 10°S latitude (Matthews, 1983). Similarly, the highest concentrations of soil carbon occur between cool temperate and polar regions (Post et al., 1982). Annual liberation of as little as 1% per year of either the 300 Pg C stored in the top meter of soils above the 60° latitude band (Zinke et al., 1984) or the estimated 500 Pg C in peat (Houghton et al., 1985) would generate a doubling of the current rate of increase of atmospheric CO_2.

Irregular distributions of terrestrial carbon may respond in a complex fashion to climate changes expected from increasing atmospheric CO_2 concentrations (Schlesinger and Mitchell, 1985). For example, the areal cover of some vegetation zones may increase or decrease depending on geography (Emanuel et al., 1985a and 1985b; Solomon, 1986). In particular, complexities in response are expected from the greater warming and longer growing seasons anticipated at high latitudes and the decreased soil moisture in continental regions (Manabe and Wetherald, 1987). Forests, which store over 80% of the earth's living terrestrial carbon, may eventually decrease slightly in areal cover (Emanuel et al., 1985b) producing no destabilizing feedbacks; however, an initial forest response is likely to be dominated by mortality of 20 to 100% of the trees in a given region, as changing climatic conditions become less like those to which existing trees are adapted (Solomon, 1986).

Warming at high latitudes could affect carbon locked in permafrost, peat, and organic soils. Billings et al. (1983) demonstrate that as permafrost melts, soil microorganisms respire and liberate large amounts of CO_2. Olson et al. (1985) suggest that global peat accumulation rates have been greater during the past 2000 years when temperatures were cooler.

Will shifts in the hydrologic cycle in response to changing climate alter global carbon fluxes?

PROBLEM: Response of the landscape water balance to CO_2-induced climate changes may change carbon sink properties due to shifting distributions of saturated soils. Reduced soil saturation in areas of large soil organic pools (e.g., wetlands) would increase decomposition rates and the release of CO_2 from these systems. CO_2-induced changes in the hydrological cycle may also affect the productivity and organic carbon sinks in estuarine and coastal ocean ecosystems. Reduced river flow resulting from CO_2-induced drought may reduce nutrient input to estuarine and coastal ocean systems, thereby reducing CO_2 uptake in these highly productive

systems that are controlled primarily by inputs from rivers. In addition, river flow influences the circulation patterns of estuarine and coastal ocean systems and, in turn, the deposition and accumulation of sediment organic carbon.

KNOWNS, UNKNOWNS, UNCERTAINTIES: Historically, wetland soils have accumulated carbon at a rate of about 0.14 Pg Cyr^{-1} across the globe (Armentano et al., 1984). The total pool of carbon in poorly drained wetland soils is estimated to be about 500 Pg C (Olson et al., 1985). Therefore, even a 1% release of this pool per year from reduced soil saturation would result in a 5 Pg Cyr^{-1} increase. The carbon flux between these systems and the atmosphere would result in doubling the current rate of atmospheric CO_2 increase.

Accumulation of organic carbon in estuarine and coastal ocean sediments is not well documented, but it is probably in the range of 1.0 to 7.0 Pg Cyr^{-1} based on work of Wollast and Billen (1981), Dawes (1981), Walsh (1984), Peterson and Melillo (1984), and Baes et al. (1985). River flow could change by as much as 25% (Mitchell, 1983) which, in turn, could result in substantial changes in nutrient input or alteration in coastal circulation patterns influencing nutrient upwelling and organic carbon deposition and accumulation rates or both. The direct effect of a 25% reduction in flow could reduce carbon sequestering by 0.25 to 2 Pg Cyr^{-1}. Additional indirect and interacting effects could also be important, but are not known.

Will land-use shifts in response to changing climate alter terrestrial carbon fluxes?

PROBLEM: Human response to a warmer earth is likely to result in increased conversion of carbon-rich forests to carbon-poor agriculture or other non-forest uses at high and low latitudes. The land-use shifts would liberate large amounts of CO_2 and increase evapotranspiration and albedo, enhancing climate response to atmospheric CO_2 changes.

KNOWNS, UNKNOWNS, UNCERTAINTIES: The corn belt of the central United States could expand into forested areas of the northern midwest and southern Canada in response to CO_2-induced climate change (Blasing and Solomon, 1984). Large forested areas of northern Canada could be capable of growing wheat under warming induced by doubled atmospheric CO_2 (Rosenzweig, 1985). However, these studies did not consider the CO_2 fertilization effect, suitability of soil, and other nonclimatic factors. During the next 100 years, vegetative cover of the globe may be as strongly affected by clearing of new arable land in response to climate change as by the climate changes themselves (Clark et al., 1986).

Tropical forests, which contain the globe's greatest densities of terrestrial carbon, continue to be converted to low carbon-density farmland. Should climate change induce crop losses of global significance, local populations would require increased rates of tropical clearing for agriculture.

Type of land cover (e.g., crop and pasturelands, urban areas, forests, deserts, and water surfaces) determines evapotranspiration. As climate forces changes in land use and vegetation cover, evapotranspiration also changes, which, in turn, can modify climate. Climate sensitivity experiments using models suggest that enhanced evapotranspiration can induce precipitation declines and temperature increases (Shukla and Mintz, 1982). Large historic changes in vegetation due to land use are already suspected of inducing droughtier conditions (Wang et al., 1985). Future climate shifts could extend such trends, enhancing atmospheric CO_2 concentrations as vegetation disappears.

Land cover also controls global surface reflectivity (albedo). Independent atmospheric GCM experiments involving shifting albedo values indicate that increased regional albedo (from replacement of dark-colored trees with light-colored farmland) lead to a pronounced decline in precipitation (Ellsaesser et al., 1976; Charney et al., 1977; and Chervin, 1979). This process could further enhance terrestrial carbon losses.

What additional knowledge of carbon cycle processes is needed to accurately estimate the contribution of fossil fuel burning to the level of CO_2 in the atmosphere?

Gaps exist in the understanding of the global carbon cycle that make projections of future atmospheric CO_2 levels highly uncertain. Further studies could reveal factors affecting the carbon cycle that are individually or collectively as important in projecting future atmospheric CO_2 levels as the better documented factors in research questions 1 and 2. Hence, research should be undertaken to increase the fundamental understanding of the CO_2 cycle in areas where that research may be important in predicting future atmospheric CO_2 concentrations. This may include a combination of theory, analysis of available data, additional measurements, and archival research.

There are three general areas where deficiencies in current knowledge may significantly affect the accuracy of atmospheric CO_2 projections: (a) not all fluxes of CO_2 are known or quantified; (b) important buffering processes and their effects on the atmospheric concentration of CO_2 have not yet been adequately characterized; and (c) natural cycles and fluctuations of atmospheric CO_2 are not completely understood and are difficult to differentiate from anthropogenic changes.

How much of the uncertainty in predicting atmospheric CO_2 concentrations is due to incorrect estimates of carbon fluxes?

PROBLEM: The inability to account for all of the CO_2 estimated to have been released into the atmosphere by fossil fuel burning and land-use changes has limited the capability for predicting atmospheric CO_2 concentrations. On the basis of current estimates of carbon fluxes, missing fluxes to sinks of about 0.6 to 3.4 Pg Cyr^{-1} are needed to balance the fossil fuel releases for 1980 (Trabalka et al., 1985; see Detweiler and Hall, 1988, for alternative calculations). While the three-dimensional modeling of the oceans may reveal higher estimates of net atmosphere-to-ocean flux, and thus account for some of the removal of CO_2 from the atmosphere, fluxes to other sinks must also play a significant role.

KNOWNS, UNKNOWNS, UNCERTAINTIES: Some of the excess fossil fuel carbon may be accumulating in terrestrial organic matter. Accumulations of carbon in peatland and wetland soils in prehistoric times have been estimated at between 0.14 Pg Cyr^{-1} (Armentano, 1980) and 0.3 Pg Cyr^{-1} (Miller, 1981). Production of carbon-inert charcoal by anthropogenic burning of large land areas has been suggested as a process causing long-term storage of carbon. Estimates of charcoal formation of 0.3 to 1.3 Pg Cyr^{-1} were made by Seiler and Crutzen (1980), while Brown and Lugo (1984) and Detweiler et al. (1985) gave estimates of 0.2 to 0.7 Pg Cyr^{-1}. Net storage of carbon (possibly as high as 0.1 Pg Cyr^{-1}) may be occurring for certain vegetation types, such as boreal tundra (Miller, 1981; and Billings et al., 1982) and in some tropical forests (Lugo, 1983). Recent eutrophication of freshwater, estuarine, and coastal ocean ecosystems could have considerably increased organic carbon storage in inland and coastal sediments [0.5 to 1.5 Pg Cyr^{-1} (Mulholland, 1981; Wollast, 1983; and Walsh, 1984)]. The sum of these estimates ranges from 0.9 to 2.6 Pg, Cyr^{-1} representing a sizable uncertainty.

How do buffering processes explain changes in CO_2 concentrations?

PROBLEM: Buffering processes are defined here to mean those processes that respond to increasing atmospheric CO_2 by increasing the rate of removal of CO_2 from the atmosphere. The problem is to determine how the important buffering processes work and how they will respond to increasing atmospheric CO_2 to produce fluxes of carbon into various long and short term storage pools.

KNOWNS, UNKNOWNS, UNCERTAINTIES: A potentially important buffering process is the effect of CO_2 fertilization on growth rates of plants. Growth chamber experiments show increased CO_2 has enhanced growth and water-use efficiency of some plant species. This increase may be moderated in the field by limitations in other resources, competition, and other total ecosystem effects; but some increase

in the rate of photosynthesis can be expected if atmospheric CO_2 increases while climate stays constant. For example, short- term experiments with annual species of C_3 photosynthetic pathway type show that growth and productivity increase by 30 to 50% under a doubling of atmospheric CO_2 in controlled environments, in the absence of other growth constraints (Strain and Cure, 1985). However, the herbaceous plant communities of the globe contain little stored carbon [<20% of global terrestrial carbon (Olson et al., 1983)]. More relevant to the global carbon cycle are forest trees during long time periods. No field data on carbon fertilization of forest communities exist. Long-term experiments with tundra plants under field conditions have yet to demonstrate any significant increase in carbon sequestering (Oechel and Strain, 1985).

A marine example of a buffering process is the so-called biological pump effect of biological productivity. The sinking of biogenic detritus decreases CO_2 concentration in the surface waters, allowing greater uptake of CO_2 from the atmosphere. Whether biological productivity in the ocean will increase with increasing CO_2 levels, and thus increase the rate of biological pumping, depends on the degree to which this production is limited by other factors, such as nutrient availability. The assumption of steady state has been a convenience in analyses of the global carbon cycle; however, consideration must be given to the more general case where this condition does not hold.

What are the natural cycles and fluctuations in atmospheric CO_2?

PROBLEM: Ice core and tree ring data suggest that there were fluctuations in atmospheric CO_2 long before humans began to influence the global carbon cycle. Because these fluctuations may have effects on current changes in atmospheric CO_2, the mechanisms regulating these natural fluctuations, as well as possible fluctuations caused by anthropogenic activity, must be better understood.

KNOWNS, UNKNOWNS, UNCERTAINTIES: Since the last ice age, ice core records indicate ±10 ppmv variations of atmospheric CO_2 on 100-year time scales, whereas tree ring data indicate 20- to 50-ppmv variations. The latter estimate may reflect local conditions on plant growth rather than global conditions (Gammon et al., 1985).

Several possible causes for natural fluctuations have been suggested. For example, changes in sea levels and in ocean mixing in response to past climatic changes may have led to net CO_2 fluxes from the ocean to the atmosphere (Broecker and Takahashi, 1984). Direct chemical effects of ocean warming by air

warming were probably small, but these changes coupled with other climatic changes could also have indirectly affected the mixing rates and nutrient budgets of oceans and, thus, the biological fluxes in the oceans.

Long-term fluctuations or trends in terrestrial net primary productivity or decomposition could produce significant changes in the net flux with the atmosphere over decades or centuries. Woodwell (1983) estimated that a 0.5°C temperature rise could increase total respiration by 10 to 15% or approximately 10 Pg C to 15 Pg Cyr^{-1}, globally. If NPP does not match this increase during that time, then the terrestrial release might exceed the release of carbon from fossil fuel combustion. It is not clear whether recent climatic changes have affected large enough land regions to influence global flux rates. However, longer-term drought cycles of 20 or so years may cause periodic natural changes in fluxes (Olson et al., 1985). Some periodic variations, such as the El Niño-Southern Oscillation phenomenon, are also known to occur on time scales of a few years. The steady-state assumption implicit in most global carbon cycle research has been questioned based on the possibility of such variation in major carbon fluxes (Houghton et al., 1985; and Houghton, 1987).

Summary

The questions identified in this paper should not be thought of as all inclusive. We have tried to capture what we consider to be the key problems that need to be resolved to reduce ambiguities associated with predicting future atmospheric CO2 concentrations. We expect and hope for improvements in our understanding of carbon cycle processes. Hence, we welcome new suggestions and challenges to our evaluation of what information is needed to make projections of atmospheric CO_2 concentrations.

Acknowledgements

This publication is based on research supported by the Carbon Dioxide Research Program, Atmospheric and Climate Research Division, Office of Health and Environmental Research, U.S. Department of Energy under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc. Publication number 3467 of the Environmental Sciences Division, Oak Ridge National Laboratory.

Literature Cited

Armentano, T. V. 1980. Drainage of organic soils as a factor in the world carbon cycle. Bioscience 30:825-830.

Armentano, T. V., E. S. Menges, J. Molofsky, and D. J. Lawler. 1984. Carbon Exchange of Organic Soil Ecosystems of the World. Holcomb Research Institute Paper #27. Butler University, Indianapolis.

Baes, C. F., A. Björkström, and P. J. Mulholland. 1985. Uptake of carbon dioxide by the oceans. pp. 81-111. IN J. R. Trabalka (ed.), Atmospheric Carbon Dioxide and the Global Carbon Cycle. DOE/ER-0239. Carbon Dioxide Research Division, U.S. Department of Energy, Washington D.C.

Billings, W. C., J. O. Luken, D. A. Mortensen, and K. M. Peterson. 1982. Arctic tundra: A source or sink for atmospheric carbon dioxide in a changing environment. Oecologia 53:7-11.

Billings, W. C., J. O. Luken, D. A. Mortensen, and K. M. Peterson. 1983. Increasing atmospheric carbon dioxide: Possible effects on artic tundra. Oecologia 58:286-289.

Blasing, T. J., and A. M. Solomon. 1984. Response of the North American corn belt to climatic warming. Progress in Biometeorology 3:311-321.

Bolin, B. 1986. How much CO2 will remain in the atmosphere? pp. 93-155. IN B. Bolin, B. R. Döös, and J. Jäger (eds.), The Greenhouse Effect, Climatic Change, and Ecosystems. SCOPE 29. John Wiley, Chichester.

Bolin, B., E. T. Degens, P. Duvigneaud, and S. Kempe. 1979. The global biogeochemical carbon cycle. pp. 1-56. IN

Broecker, W. S., and T.-H. Peng. 1982. Tracers in the Sea. 690 pp. Eldigio Press, Palisades, New York.

Broecker, W. S., and T.-H. Peng. 1986. Carbon cycle: 1985, Glacial to interglacial changes in the operation of the global carbon cycle. Radiocarbon 28(2A):309-327.

Broecker, W. S., and T. Takahashi. 1984. Is there a tie between atmospheric CO_2 content and ocean circulation? pp. 314-326. IN J. E. Hansen and T. Takahashi (eds.) Climate Processes and Climate Sensitivity. Geophysical Union Monograph 29. American Geophysical Union, Washington, D.C.

Brown, S., and A. E. Lugo. 1982. The storage and production of organic matter in tropical forests and their role in the global carbon cycle. Biotropica 14:161-187.

Brown, S., and A. E. Lugo. 1984. Biomass of tropical forests: A new estimate based on volumes. Science 223:1290-1293.

Charney, J. G., W. J. Quirk, S. Chow, and J. Cornfield. 1977. A comparative study of the effects of albedo change on drought in semi-arid regions. Journal of Atmospheric Sciences. 34:1366-1385.

Chavez, F. P., and R. T. Barber. 1987. An estimate of new production in the equatorial Pacific. Deep Sea Research. (in press).

Chervin, R. M. 1979. Response of the NCAR atmospheric general circulation model to changed albedo. pp. 563-581. IN Report of the JOC Study Conference on Climate Models: Performance, Intercomparison, and Sensitivity Studies. GARP Publication Series Number 22, World Meteorological Organization, Geneva.

Clark, W. C., J. Richards, and E. Flint. 1986. Human transformation of the earth's vegetation cover: Past and future impacts of agricultural development and climatic change. pp. 54-59. IN C. Rosenzweig and R. Dickinson eds.), Climate-Vegetation Interactions. University Corporation for Atmospheric Research, Boulder, Colorado.

Dawes, C. J. 1981. Marine Botany. Wiley & Sons, New York.

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

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

DeVooys, C. G. N. 1979. Primary production in aquatic environments. pp. 259-292. IN B. Bolin, E. T. Degens, S. Kempe, and P. Ketner (eds.), The Global Carbon Cycle. SCOPE 13. John Wiley, Chichester.

Ellsaesser, H. W., M. C. MacCracken, G. L. Potter, and F. M. Luther. 1976. An additional model test of positive feedback from high desert albedo. Quarterly Journal of the Royal Meteorlogical Society 102:655-666.

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

Emanuel, W. R., I. Fung, G. G. Killough, B. Moore, and T.-H. Peng. 1985a. Modeling the global carbon cycle and changes in the atmospheric carbon dioxide levels. IN J. R. Trabalka (ed.), Atmospheric Carbon Dioxide and the Global Carbon Cycle, DOE/ER-0239, U.S. Department of Energy, Washington, D.C.

Emanuel, W. M., H. H. Shugart, and M. P. Stevenson. 1985b. Climate change and the broad scale distribution of terrestrial ecosystem complexes. Climatic Change 7:29-43.

Eppley, R. W., and B. J. Peterson. 1979. Particulate organic matter flux and plantonic new production in the deep ocean. Nature 282:677-680.

Food and Agriculture Organization of the United Nations (FAO). 1983. Production Yearbook. FAO, Rome.

Gammon, R. H., E. T. Sundquist, and P. J. Fraser. 1985. History of carbon dioxide in the atmosphere. pp. 25-62. IN J. R. Trablaka (ed.), Atmospheric Carbon Dioxide and the Global Carbon Cycle. DOE/ER-0239. Carbon Dioxide Research Division, U.S. Department of Energy, Washington, D.C.

Houghton, R. A., J. E. Hobbie, J. M. Melillo, B. Moore, B. J. Peterson, G. R. Shaver, and G. M. Woodwell. 1983. Changes in the carbon content of terrestrial biota and soils between 1860 and 1980: Net release of CO2 to the atmosphere. Ecological Monographs 53:235-262.

Houghton, R. A., W. H. Schlesinger, S. Brown, J. F. Richards. 1985. Carbon dioxide exchange between the atmosphere and terrestrial ecostystems. pp. 113-140. IN J. R. Trabalka (ed.) Atmospheric Carbon Dioxide and the Global Carbon Cycle. DOE/ER-0239. Carbon Dioxide Research Division, U.S. Department of Energy, Washington, D.C.

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. Myers. 1987. The flux of carbon from terrestrial ecosystems to the atmosphere in 1980 due to changes in land use: Geographic distribution of global flux. Tellus 39B:122-139.

Kasting, J. F., and T. P. Ackerman. 1986. Climatic consequences of very high carbon dioxide levels in the earth's early atmosphere. Science 234:1383-1385.

Killough, G. G., and W. R. Emanuel. 1981. 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.

Knox, F., and M. B. McElroy. 1984. Changes in atmospheric CO2: Influence of the marine biota at high latitudes. Journal of Geophysical Research 89:4629-4637.

Lugo, A. E. 1983. Influence of green plants on the world carbon budget. pp. 391-396. IN T. N. Veziroglu (ed.), Alternative energy sources. V. Part E: Nuclear/conservation/ environment. Elsevier Science Publishing, Amsterdam, The Netherlands.

Luther, F. M. 1985. Projecting the climatic effects of increasing carbon dioxide: Volume summary. pp. 259-272. IN M. C. MacCracken and F. M. Luther (eds.), The Potential Climatic Effects of Increasing Carbon Dioxide, DOE/ER-0237, U. S. Department of Energy, Washington D.C.

MacCracken, M. C. 1985. Carbon dioxide and climate change: Background and overview. pp. 1-23. IN M. C. MacCracken and F. M. Luther (eds.), Increasing Carbon Dioxide, DOE/ER-0237, U. S. Department of Energy, Washington D.C.

Manabe, S., and R. T. Wetherald. 1987. Large scale changes of soil wetness induced by an increase in atmospheric carbon dioxide. Journal of Atmospheric Sciences. 44:1211-1235.

Mann, L. K. 1985. A regional comparison of carbon in cultivated and uncultivated Alfisols and Mollisols in the central United States. Geoderma 36:241-253.

Mann, L. K. 1986. Changes in soil carbon storage after cultivation. Soil Science 142:279-288.

Martin, J. H., G. A. Knauer, D. M. Karl, and W. W. Broenkow. 1987. VERTEX: Carbon cycling in the norhteast Pacific. Deep Sea Res. 34:267-285.

Maybeck, M. 1981. River transport of organic carbon to the ocean. U.S. Department of Energy Carbon Dioxide Effects Research and Assessment Program. Conference 8009140 UC-11.

McElroy, M. 1983. Marine biological controls on atmospheric CO2 and climate. Nature 302:328-329.

Melillo, J. M., J. Fruci, R. A. Houghton, and B. Moore. 1988. Land-use change in the Soviet Union between 1850 and 1980: Causes of a net release of CO_2 to the atmosphere. Tellus 40B:116-128.

Miller, P. C. 1981. Carbon balance in northern ecosystems and the potential effect of carbon dioxide induced climate change. U.S. Department of Energy, Washington, D.C.

Mitchell, J. F. B. 1983. The seasonal response of a general circulation model to changes in CO2 and sea temperatures. Quarterly Journal of the Royal Meteorlogical Society 109:113-152.

Molofsky, J., C. A. S. Hall, and N. Myers. 1986. A comparison of tropical forest surveys. DOE/NBB-0078, U.S. Department of Energy, Washington, D.C.

Mulholland, P. J. 1981. Inland aquatic ecosystems and the perturbed global carbon cycle (ORAU/IEA-81-7M). Oak Ridge Associated Universities, Oak Ridge, Tennessee.

Myers, N. 1980. Conversion of Tropical Moist Forests. National Research Council, Washington, D.C.

Myers, N. 1984. The Primary Source. Tropical Forests and Our Future. Norton, London.

Neftel, A., H. Oeschger, J. Schwander, B. Stauffer, and R. Zumbrunn. 1982. Ice core sample measurements give atmospheric CO2 content during the past 40,000 years. Nature 295:220-223.

Oechel, W., and B. R. Strain. 1985. Native species responses to increased carbon dioxide concentration. IN B. R. Strain, and J. D. Cure (eds.), Direct Effects of Increasing Carbon Dioxide in Vegetation. DOE/ER-0238.

Oeschger, H., and B. Stauffer. 1986. Review of the history of atmospheric CO_2 recorded in ice cores. pp. 89-108. IN J. R. Trabalka and D. E. Reichle (eds.), The Changing Carbon Cycle: A Global Analysis. Springer-Verlag, New York.

Olson, J. S., J. A. Watts, and L. J. Allison. 1983. Carbon in live vegetation of major world ecosystems. ORNL-5862, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Olson, J. S., R. M. Garrels, R. A. Berner, T. V. Armentano, M. I. Dyer, and D. H. Yaalon. 1985. The natural carbon cycle. pp. 175-214. IN J. R. Trabalka (ed.), Atmospheric Carbon Dioxide and the Global Carbon Cycle. DOE/ER-0239, U.S. Department of Energy, Washington, D.C.

Pastor, J., and W. M. Post. 1986. Influence of climate, soil moisture, and succession on forest carbon and nitrogen cycles. Biogeochemistry 2:3-27.

Peng, T.-H., W. S. Broecker, H. D. Freyer, and S. Trumbore. 1983. A deconvolution of the tree rings based $\delta^{13}C$ record. J. Geophysical Research 88:3609-3620.

Peng, T.-H., and W. S. Broecker. 1984. Ocean life cycles and the atmospheric CO_2 content. Journal of Geophysical Research 89:8170-8180.

Peng, T.-H., and H. D. Freyer. 1986. Revised estimates of atmospheric CO2 variations based on the tree-ring 13C record. pp. 151-159. IN J. R. Trabalka, and D. E. Reichle (eds.). The Changing Carbon Cycle: A Global Analysis. Springer-Verlag, New York.

Peterson, B. J., and J. M. Melillo. 1984. Global carbon-nitorgen-phosphorus cycle interactions: A key to solving the atmopsheric CO_2 balance problem. pp. 97-115. IN B. Moore III and M. N. Dastoor (eds.), The Interaction of Global Biochemical Cycles (JPL Publication 84-21). U. S. National Aeronautics and Space Administration, Pasadena, California.

Post, W. M., W. R. Emanuel, P. J. Zinke, and A. G. Stangenberger. 1982. Soil carbon pools and world life zones. Nature 298:156-159.

Rosenberg, N. J. 1981. The increasing CO2 concentration in the atmosphere and its implications on agricultural productivity. Climatic Change 3:265-279.

Rosenzweig, C. 1985. Potential CO_2-induced climate effects on North American wheat-producing regions. Climatic Change.

Rotty, R. M. 1987. Estimates of seasonal variation in fossil fuel CO_2 emissions. Tellus 39B:184-202.

Sarmiento, J. L., and J. R. Toggweiler. 1984. A new model for the role of the oceans in determining atmospheric pCO2. Nature 308:621-624.

Schlesinger, W. H. 1986. Changes in soil carbon and associated properties with disturbance and recovery. pp. 194-220. IN J. R. Trabalka and D. E. Reichle (eds.), The Changing Carbon Cycle: A Global Analysis. Springer-Verlag, New York.

Schlesinger, W. H., and J. M. Melack. 1981. Transport of carbon in the world's rivers. Tellus 33:172-187.

Schlesinger, M. E., and J. F. B. Mitchell. 1985. Model projections of the equilibrium climatic response to increased carbon dioxide. pp. 81-148. IN M. C. MacCracken and F. M. Luther (eds.), Projecting the Climatic Effects of Increasing Carbon Dioxide, DOE/ER-0237, U.S. Department of Energy, Washington, D.C.

Seiler, W., and P. J. Crutzen. 1980. Estimates of gross and net fluxes of carbon between the biosphere and atmosphere from biomass burning. Climatic Change 2:207-247.

Shukla, J., and Y. Mintz. 1982. Influence of land-surface evapotranspiration on the earth's climate. Science 215:1498-1500.

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

Siegenthaler, U. and T. Wenk. 1984. Rapid atmospheric CO2 variations and ocean circulation. Nature 308:624-626.

Solomon, A. M. 1986. Transient response of forests to CO2-induced climate change: Simulation modeling experiments in eastern North America. Oecologia 68:567-579.

Solomon, A. M., and M. L. Tharp. 1985. Simulation experiments with late quaternary carbon storage in mid-latitude forest communities. pp. 235-249. IN E. T. Sundquist and W. S. Broecker (eds.), The Carbon Cycle and Atmospheric CO2: Natural Variations Archean to Present (American Geophysical Union Monograph 32) American Geophysical Union, Washington D.C.

Strain, B., and J. Cure. 1985. Direct effects of increasing carbon dioxide on vegetation (DOE/ER-0236). U.S. Department of Energy, Washington, D.C. Available from NITS, Springfield, Virginia.

Sundquist, E. T. 1985. Geological perspectives on carbon dioxide and the carbon cycle. IN E. T. Sundquist and W. S. Broecker (eds.), The Carbon Cycle and Atmospheric CO2: Natural Variations Archean to Present (American Geophysical Union Monograph 32), American Geophysical Union, Washington, D.C.

Sundquist, E. T. 1986. Geologic analogs: Their value and limitation in carbon dioxide research. pp. 371-402. IN J. R. Trabalka and D. E. Reichle (eds.), The Changing Carbon Cycle: A Global Analysis. Springer-Verlag, New York.

Takahashi, T., J. Olafsson, W. S. Broecker, J. Goddard, D. W. Chipman, and J. White. 1985. Seasonal variability of the carbon-nutrient chemistry in the oceanic areas west and north of Iceland. pp. 20-36. IN U. Stefansson (ed.), Chemical Tracers for Studying Water Masses and Physical Processes in the Seas. Rit Fiskideilder, Journal of the Marine Research Institute 9:20-36, Reykjavik.

Takahashi, T., J. Goddard, S. Sutherland, D. W. Chipman, and C. C. Breeze. 1986. Seasonal and geographic variability of carbon dioxide sink/source in the oceanic areas: Observations in the north and equatorial Pacific Ocean, 1984-1986 and global summary. Final Technical Report for Contract, MRETTA 19X-89675C to DOE CDRD.

Trabalka, J. R., J. A. Edmonds, J. M. Reilly, R. H. Gardner, and L. D. Voorhees. 1985. Human alterations of the global carbon cycle and the projected future. pp. 247-288. IN J. R. Trabalka (ed.), Atmospheric Carbon Dioxide and the Global Carbon Cycle. DOE/ER-0239. U.S. Government Printing Office, Washington, D.C.

Walsh, J. J. 1984. The role of ocean biota in accelerated ecological cycles: A temporal view. Bioscience 34:499-507.

Wang, W.-C., D. J. Wuebbles, and W. M. Washington. 1985. What past climates can indicate about a warmer world. pp. 191-235. IN M. C. MacCracken and F. M. Luther (eds.), The Potential Climatic Effects of Increasing Carbon Dioxide. DOE/ER-0237, U.S. Department of Energy, Washington D.C.

Wollast, R. 1983. Interactions in estuaries and coastal waters. pp. 385-410. IN B. Bolin and R. B. Cook (eds.), The Major Biogeochemical Cycles and Their Interactions. SCOPE 23. Springer-Verlag.

Wollast, R., and G. Billen. 1981. The fate of terrestrial organic carbon in the coastal area. pp. 331-359. IN Carbon Dioxide Effects Research an Assessment Program, CONF-8009140, U.S. Department of Energy, Washington, D.C.

Woodwell, G. M. 1983. Biotic effects on the concentration of atmospheric carbon dioxide: A review and projection. IN Changing Climate. National Academy Press, Washington D.C.

Zinke, P. J., A. G. Stangenberger, W. M. Post, W. R. Emanuel, and J. S. Olson. 1984. Worldwide Organic Soil Carbon and Nitrogen Data (ORNL/TM-8857). Oak Ridge National Laboratory, Oak Ridge, Tennessee.