INTERNATIONAL ATOMIC ENERGY AGENCY
UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION
INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
I.C.T.P., P.O. BOX 586, 34100 TRIESTE, ITALY, CABLE: CENTRATOM TRIESTE

SMR.780 - 39

FOURTH AUTUMN COURSE ON MATHEMATICAL ECOLOGY

(24 October - 11 November 1994)

"The Global Carbon Cycle"

Wilfred M. Post, Tsung-Hung Peng, William R. Emanuel, Anthony W. King, Virginia H. Dale and Donald L. DeAngelis
Environmental Sciences Division
Oak Ridge National Laboratory
Oak Ridge, TN 37831-6335
U.S.A.

These are preliminary lecture notes, intended only for distribution to participants.

The Global Carbon Cycle

Wilfred M. Post, Tsung-Hung Peng, William R. Emanuel, Anthony W. King, Virginia H. Dale and Donald L. DeAngelis

More than three decades have passed since Roger Revelle and Hans Suess (1957) drew scientific attention to a planetary-scale "experiment" in which mankind is "returning to the atmosphere and oceans the concentrated organic carbon stored in sedimentary rocks over hundreds of millions of years." In the years since that warning, we have begun to grasp the significance of this unplanned and uncontrolled experiment. We are witnessing a dramatic increase in carbon dioxide in the atmosphere, and we now recognize the potential climatic impact of that increase. What began as speculation among scientists about the interactions between CO_2 and climate is today a popular subject for government reports, Congressional hearings, newspaper articles and international policy debates.

The debates are set against a backdrop of new findings about CO_2 in the atmosphere. In recent years we have gained information on the contribution of land clearing to atmospheric CO_2 levels. We have found that long-term records of atmospheric CO_2 concentrations can be obtained from ice cores. And we have better estimates of how carbon is stored and exchanged by oceanic, atmospheric and terrestrial reservoirs.

But the research of the past few years has uncovered more complexities than were previously appreciated. We are unable to balance all the fluxes of the global carbon cycle over the period from 1800 to the present, and different mathematical models give results that are hard to reconcile. Moreover, recent studies have added to our awareness of the sensitive feedback relationships between the concentration of CO_2 in the atmosphere and the terrestrial and oceanic processes that regulate exchanges with the atmosphere. The popular phrase "greenhouse effect" describes one part of the interaction between CO_2 and climate, in which a higher concentration of CO_2 is expected to bring about a global warming. Feedback processes, however, could either moderate the increase in CO_2—and thereby stabilize the global system—or turn a gradual rise into an even more rapid climb. Hence, while we can document the growing human contribution of carbon dioxide to the atmosphere, and the potential for additional increases, we are in a poor position to predict how continued increases will affect the global carbon cycle.

The dynamic responses of natural systems to CO_2 remain a puzzle—and the earth's climate may hang in the balance.

Writing in *American Scientist* in 1977, Charles F. Baes, Jr., and his colleagues accurately articulated what was then known about CO_2 and climate. In this article we present what we believe are the most important advances in carbon-cycle research since that article appeared. We take inventory of the world's carbon reservoirs, and we discuss what is known about the role of oceanic and terrestrial systems in exchanging CO_2 with the atmosphere. Finally, we describe a new global systems approach, which shows promise in resolving current difficulties.

Carbon Reservoirs and Fluxes

The carbon dioxide that makes up a small (but vitally important) constituent of the atmosphere is part of a vast planetary cycle, in which carbon cir-

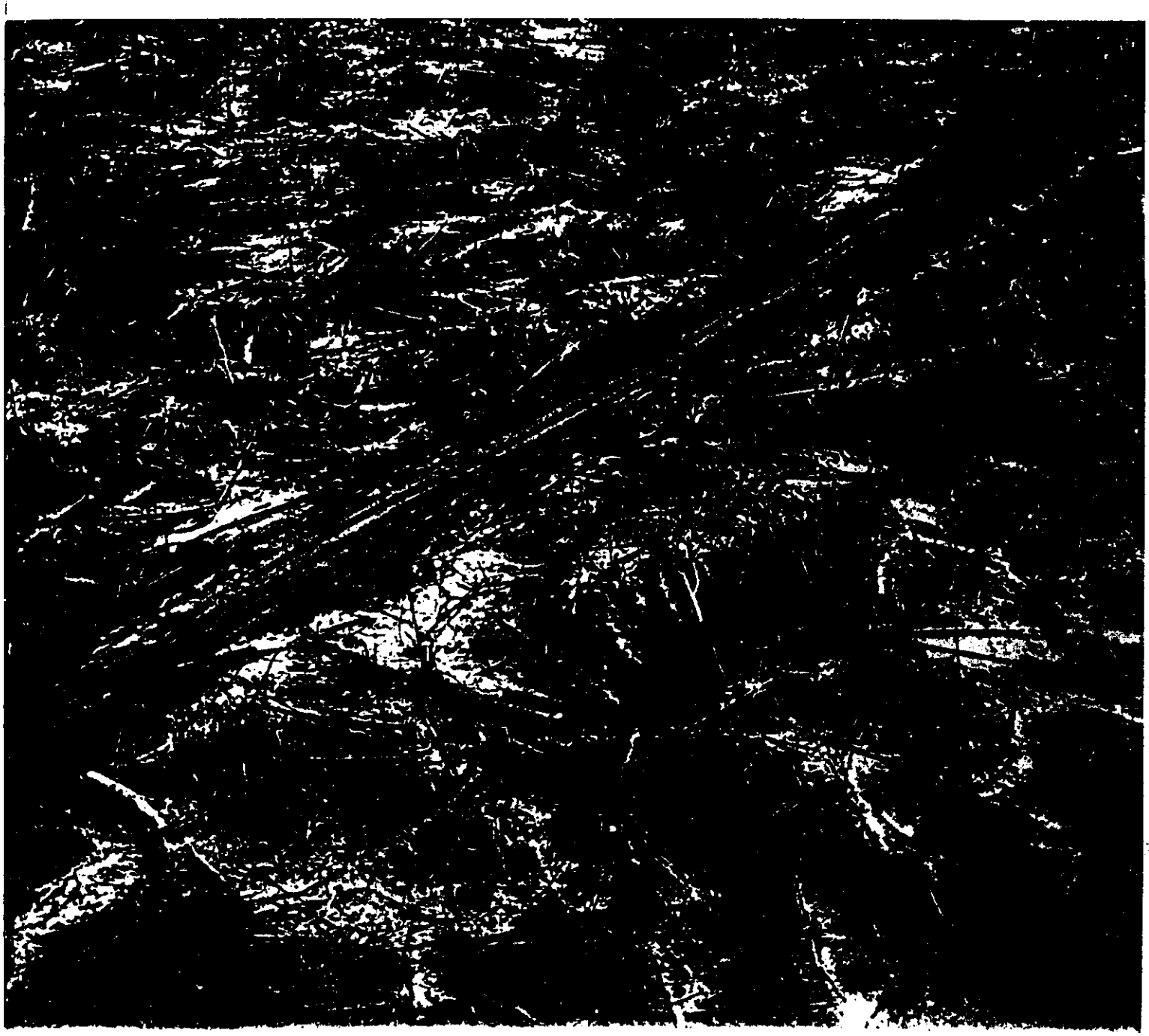
H. Silvester (Photo Researchers, Inc.)

Wilfred M. Post, Tsung-Hung Peng, William R. Emanuel, Anthony W. King, Virginia H. Dale and Donald L. DeAngelis are staff scientists with the Environmental Sciences Division of Oak Ridge National Laboratory. Post, King and Dale are ecosystem ecologists. Peng is a geochemist. Emanuel is an electrical engineer and DeAngelis is a theoretical ecologist. Address: Environmental Sciences Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831-6335.

culates among three active reservoirs and undergoes several changes of chemical form. The reservoirs are the atmosphere, the oceans and a terrestrial system that includes a variety of stocks, such as forests and the organic carbon found in soil (Figure 6). Of the three reservoirs the oceanic one contains by far the largest amount of carbon. The atmosphere is the smallest in terms of carbon storage, but it plays a significant role in the cycle as a conduit between the other two reservoirs. The flux of carbon among the reservoirs is influenced by the current inventory of carbon in each reservoir and by the turnover rates, which vary as functions of environmental factors.

The size of the atmospheric carbon reservoir has been accurately known since 1958, when Charles Keeling began continuous measurements of the atmospheric concentration of CO_2 at the Mauna Loa Observatory in Hawaii. In 1958 the average annual concentration in the atmosphere was 315 microliters of CO_2 per liter of air, which works out to a concentration of about 0.03 percent and a total of 671 gigatons (billions of metric tons) of carbon in the atmosphere. Since then the amount of carbon in the atmosphere has grown exponentially (Figure 3b). In 1988 the concentration was 351 microliters per liter, or 748 gigatons of carbon. In contrast, analysis of air trapped in polar ice shows that over the past 160,000 years, atmospheric CO_2 has varied from 200 microliters per liter at the height of the last glaciation to between 260 and 300 microliters per liter during interglacial periods. Ice-core measurements for recent times agree well with the Mauna Loa data and suggest that concentrations during the period from 1750 to 1800 were

Figure 1. Burned Amazonian rainforest, crossed by an unpaved road, suggests the impact of human activities on the global carbon cycle. As a result of deforestation, as much as 2.6 gigatons of carbon stored in vegetation returned to the atmosphere as carbon dioxide in 1980. Estimates of this flow, the size of the carbon stocks in tropical vegetation and the impact of past land-use activities on the global carbon cycle are the subjects of considerable debate.



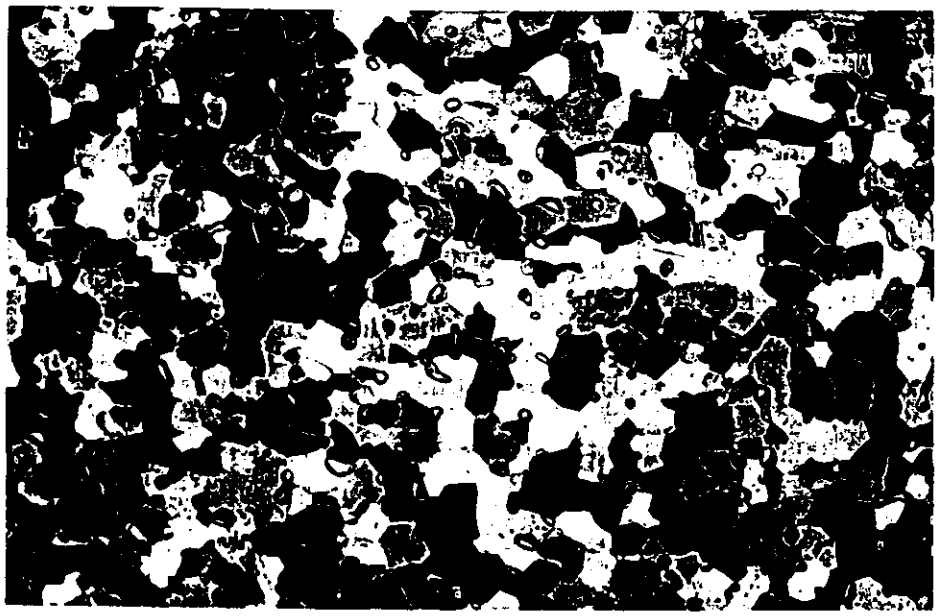


Figure 2. Trapped air bubbles, analyzed to provide a record of atmospheric CO_2 concentrations, are visible in samples of recently formed ice. This photograph, made between crossed polarizers, shows a section of a Byrd Station Antarctic ice core, half a millimeter thick and 61 millimeters across in this picture. The section was taken from a depth of 56 meters, where the trapped air is estimated to be 450 years old. The bubbles appear amber-colored and are located primarily at crystal grain boundaries. Ice-core measurements have replaced the less-reliable technique of analyzing ^{13}C in tree rings to compare current atmospheric CO_2 levels with those of the recent past. (Photograph courtesy of A. J. Gow, U.S. Army Cold Regions Research and Engineering Laboratory.)

approximately 279 microliters per liter, an important benchmark for estimating the impact of recent human activity.

The ocean stores carbon in three forms: dissolved inorganic carbon (consisting of dissolved CO_2 and the bicarbonate and carbonate ions HCO_3^- and CO_3^{2-}), dissolved organic carbon (consisting of both small and large organic molecules) and particulate organic carbon (consisting of live organisms or fragments of dead plants and animals). Based on data from the Geochemical Ocean Sections Study, about 37,000 gigatons of dissolved inorganic carbon is found in the oceans. In 1979 Kenneth Mopper and Egon Degens estimated that the oceans contain an additional 1,000 gigatons of dissolved organic carbon and 30 gigatons of particulate organic carbon. New measurement techniques, however, may substantially increase the estimates of organic carbon.

There is considerable uncertainty about how much carbon is stored on land. Estimates of the car-

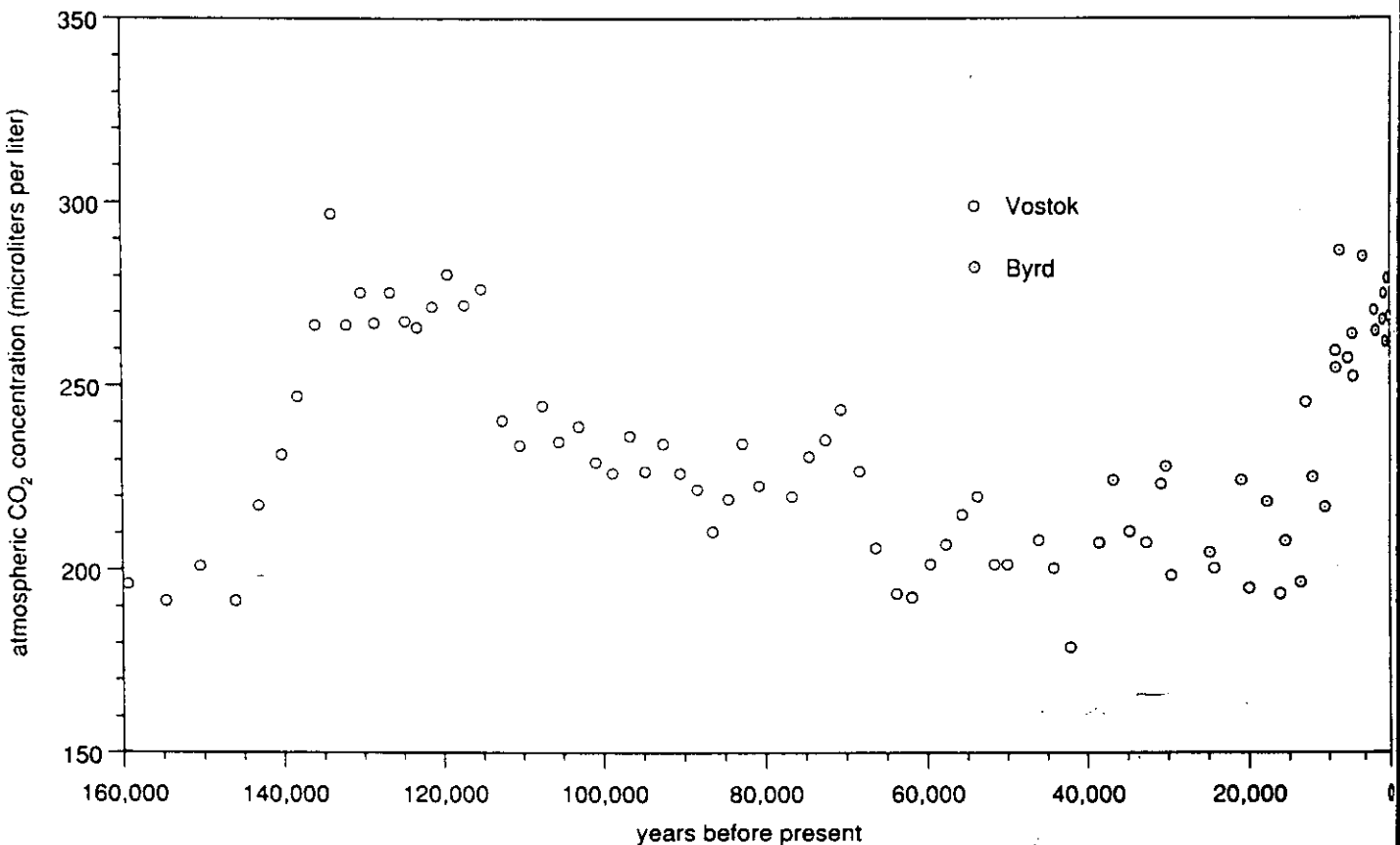


Figure 3a. Carbon dioxide concentrations in the atmosphere have varied over the glacial cycles of the earth's history, peaking at just under 300 microliters per liter of air during the interglacial period approximately 130,000 years ago and reaching that level again at the end of the last glaciation 10,000 years ago. This graph shows CO_2 measurements from air bubbles trapped in Antarctic ice sampled at Vostok and Byrd stations (Barnola et al. 1987, Neftel et al. 1982).

3.

bon in plants range widely, from 420 to 830 gigatons, depending on the methods used to classify ecosystems into types, to determine the area of each type, and to measure the carbon stocks of each type. The same problems arise in estimating the storage of carbon in litter and soil organic matter; the most probable range for soil carbon is between 1,200 and 1,600 gigatons.

Since the Industrial Revolution, people have contributed carbon to the atmosphere primarily through the burning of fossil fuels such as coal, petroleum and natural gas. This activity injects into the cycle annually a substantial amount of carbon—equivalent to 0.8 percent of the current carbon content of the atmosphere—from the earth's geological reservoir, which otherwise would not play a role in the global carbon cycle in the short term. Carbon emissions from fossil-fuel burning are estimated to have increased at a rate near 4.3 percent per year from 1860 until 1973, except for brief periods during the Great Depression and the world

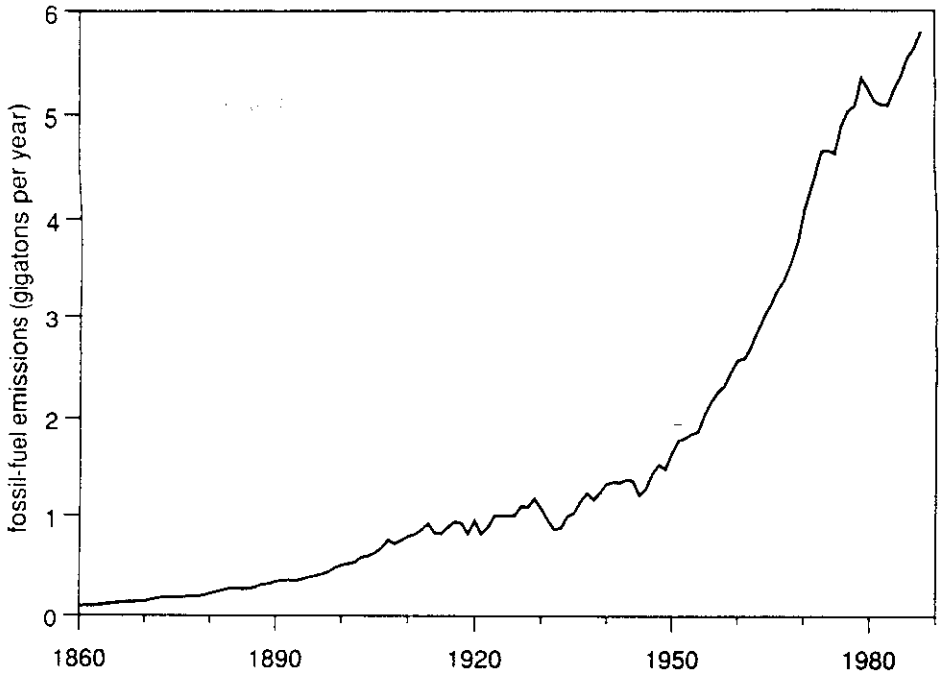


Figure 4. Fossil-fuel burning, cement production and natural-gas flaring have released increasing amounts of carbon into the atmosphere since 1860. With the exception of short periods during the Great Depression and world wars, emissions grew about 4.3 percent annually until 1973. Following the 1973 oil embargo and a decline induced by sharp oil price increases in the early 1980s, the amount of carbon entering the atmosphere in these ways resumed its steady increase in the mid-1980s and reached 5.9 gigatons in 1988 (Marland et al. 1989).

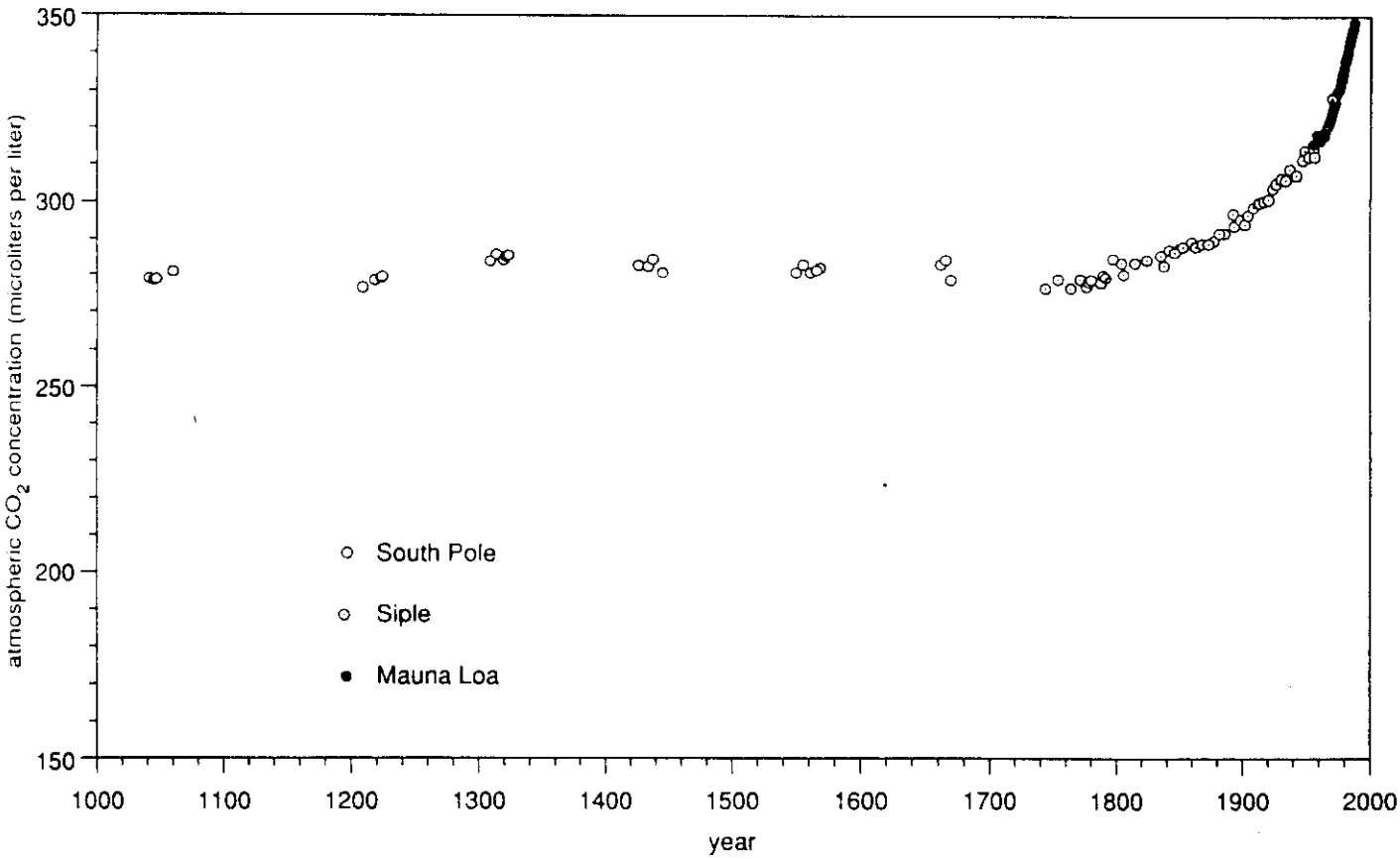


Figure 3b. Atmospheric CO_2 began increasing in the 18th century, and direct measurements made at Mauna Loa Observatory in Hawaii since 1958 indicate that the increase has accelerated. In 1988 the atmospheric carbon reservoir was estimated at 748 gigatons, equivalent to a CO_2 concentration of 351 microliters per liter and larger than at any time during the past 160,000 years. The South Pole and Siple ice-core data are from Neftel et al. 1985, Friedli et al. 1986 and Siegenthaler et al. 1988.

4.

wars. The 1973 oil embargo halted this growth, but emissions have been increasing again since the mid-1980s, and the amount of carbon contributed to the atmosphere from fossil-fuel burning was about 5.9 gigatons in 1988 (Figure 4). Remaining reserves of recoverable fossil fuels total more than 4,000 gigatons.

To evaluate the cumulative impact of fossil-fuel burning, we must place it in context with other contributions to the carbon cycle—including human land use, which transfers carbon from the terrestrial reservoir to the atmosphere. While fossil-fuel burning contributed about 5.9 gigatons of carbon to the atmosphere in 1988, the atmosphere annually exchanges more than 100 gigatons of carbon with terrestrial ecosystems and a similar amount with the world's oceans. Thus the overall flows of carbon into and out of the atmosphere amount to more than 25 percent of the total atmospheric reservoir (Figure 5).

This article will discuss these processes in terms of net fluxes—the difficult-to-measure balances and imbalances in exchanges of carbon between and within the reservoirs. Determining how human activities affect the concentration of atmospheric CO_2 requires understanding the effects of the natural fluxes and of feedbacks between increased atmospheric CO_2 and changes in these fluxes.

Ocean Mixing and Circulation

The largest pool of carbon in the world cycle, the oceanic reservoir, has a major part in determining the concentration of CO_2 in the atmo-

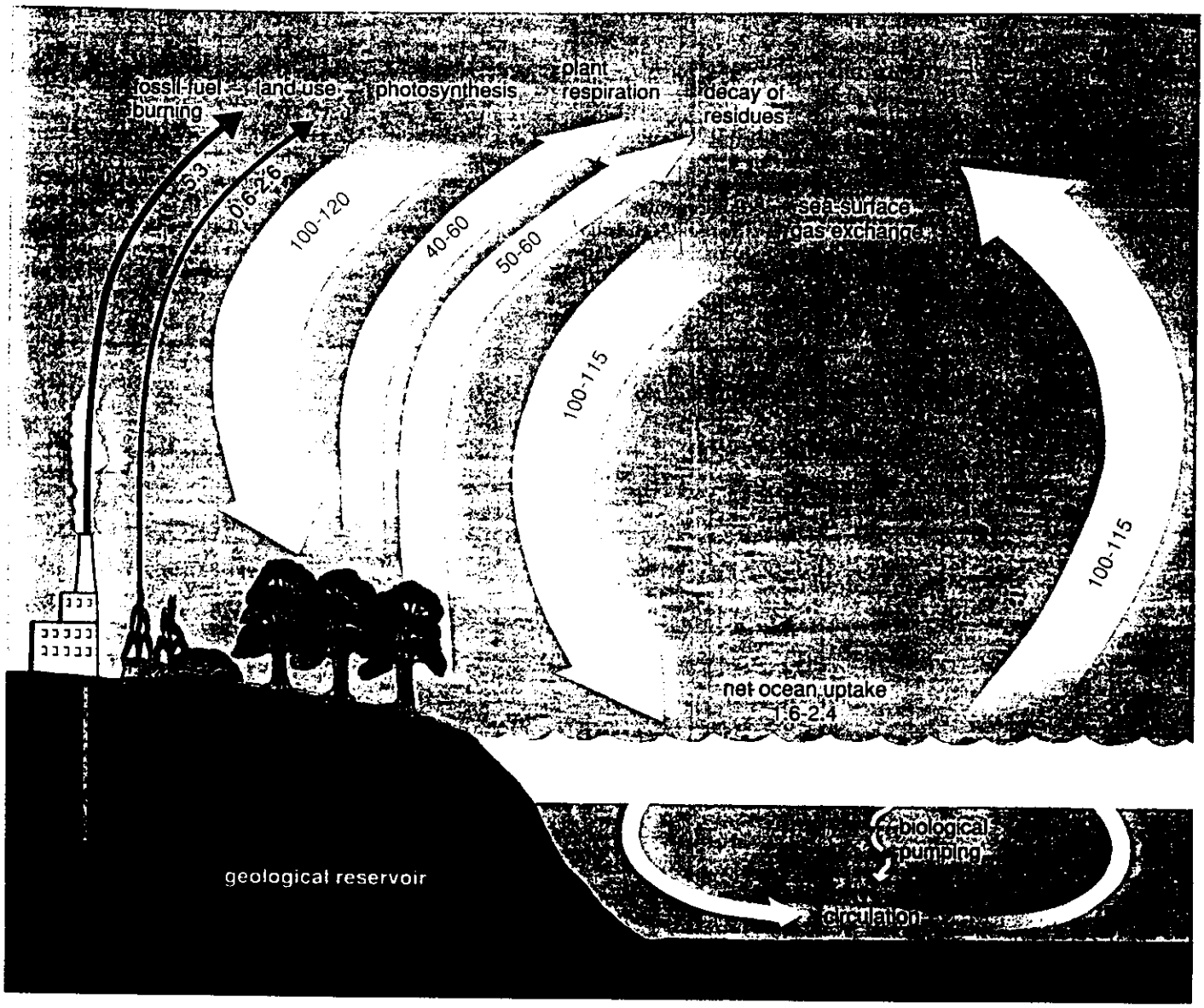


Figure 5. Massive flows between reservoirs make up the global carbon cycle. Plants on land take in carbon dioxide through photosynthesis. The terrestrial biosphere returns carbon to the atmosphere through plant respiration, the decomposition of plant residues and natural fires. The clearing of land for human activities also transfers carbon from the terrestrial system to the atmosphere. Meanwhile, gases are exchanged rapidly at the ocean surface; carbon is transferred to the deep ocean by circulation and by biological production (the use of carbon by surface organisms to produce compounds that enter the food chain of marine life). The ocean is believed to accumulate about two gigatons of carbon per year; most of this carbon is eventually dissolved in deep-ocean waters. Fossil-fuel burning transfers carbon from the geological reservoir to the atmosphere. All carbon fluxes are 1980 estimates, in gigatons.

5.

ıere through physical processes
xing and circulation), chemical
ıcesses (carbon chemistry and
fering effects) and biological pro-
ses (production and decomposi-
ı of organic matter and the forma-
ı and dissolution of carbonate
lls). Biological processes maintain
carbon structure of the oceans:
p-ocean water is richer in dis-
ed inorganic carbon than surface
er, in which the dissolved carbon
duced by photosynthesis and the
sequent sinking of the organic
ter produced. These vertical gra-
ıts help to stabilize the atmo-
eric CO_2 concentration, as does
an alkalinity, which regulates car-
ıate chemistry.

Because of the effectiveness of
ıds over the oceans' vast surface
ı, CO_2 is exchanged rapidly across
sea-air interface, resulting in an
roximate equilibrium between
partial pressures of CO_2 in the
osphere and in the surface ocean
er. As a result, little CO_2 can be
n up by surface seawater without
ocess that transfers carbon to the
per water, lowering the concen-
ion of CO_2 at the surface.

The rate at which carbon in
ın surface water is mixed into
per layers was poorly known un-
oth radioactive and stable chemi-
tracers could be used for making
mates. Since the 1970s natural ^{14}C
both tritium (^3H) and ^{14}C pro-
ed by atmospheric tests of nuclear
ıpons have served as tracers in
lies of ocean mixing and circula-
. These tracer data permit calibra-
of models of carbon turnover in
oceans. Such models typically di-
the oceans into a well-mixed
ace layer exchanging carbon with
atmosphere and with deeper wa-
, and a deep-water reservoir that
urther subdivided to represent
ing and circulation effects. The
st widely applied model based on
ı layers, or boxes, describes verti-
transfer in terms of diffusion; it
herefore called a box-diffusion
del. The calibrated model sug-
s that the net carbon uptake by
oceans lies in the range from 23 to
gigatons for the years between
3 and 1980—or 26 to 34 percent of
fossil-fuel carbon put into the
osphere during that period. This
siderable range between the up-
and lower estimates indicates
how inadequately we understand mixing processes in the ocean.

In addition to the vertical mixing emphasized by the box-diffusion model, larger-scale advective flows (currents) transport carbon in the ocean. This transport often follows contours of equal density, called isopycnals. At low and middle latitudes the densest water is at the greatest depths; at high latitudes, however, such dense waters occur at shallow depths. They can even be exposed to the atmosphere under polar low temperatures. Direct contact of excess atmospheric CO_2 with dense, cool water in polar outcrop areas such as the North Atlantic creates a shortcut for significant amounts of carbon to enter waters that sink to form the deep waters for much of the world's oceans. It is not known what fraction of excess CO_2 has entered the ocean through this process, however, because very little is known about high-latitude oceanography and deep-water formation.

Biological Pumping

In a box-diffusion model, carbon uptake is calculated by deriving a coefficient of vertical diffusivity, which is actually a surrogate for several important water-mixing effects: upwelling, downwelling, vertical diffusion, advection and the gravitational drift of biogenic materials. Understanding the ocean carbon cycle lies in determining the effects of such controlling processes, which also include biological production and destruction.

Marine life flourishes near the ocean surface. Through photosynthesis, organisms take up dissolved inorganic carbon and manufacture both inorganic compounds (such as the carbonate of foraminifera shells) and the organic matter that provides energy to the marine food chain. Many of the substances created through this process, which is called primary production, sink to the deeper ocean, often in the form of fecal pellets and dead organisms. The sinking materials undergo remineralization and bacterial decomposition, and a minor fraction is deposited on the floor of the open ocean. The transport mechanism that carries carbon from the upper ocean to deep waters is called biological pumping.

The rate at which biological pumping transfers organic material from the surface to the deeper ocean is called new production. New production is hard to measure directly, and therefore it is estimated as 15 to 20 percent of net primary production (carbon assimilated through photosynthesis less what is released by respiration of photosynthetic organisms). Until recently, the magnitude

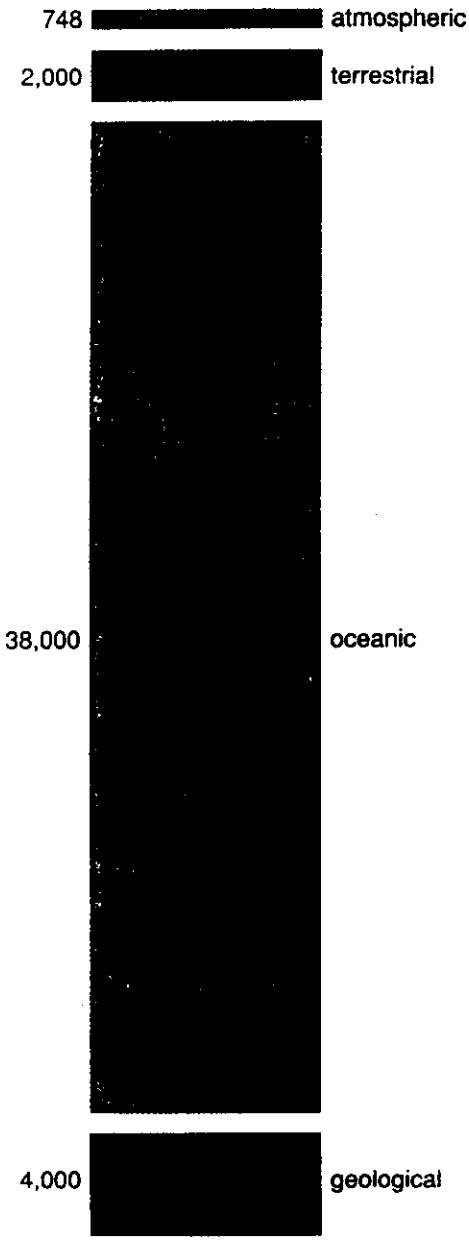


Figure 6. Major active reservoirs in the natural global carbon cycle are the oceans, terrestrial system and atmosphere. The oceans are the largest active reservoir; the atmosphere, the smallest. Geological stores of recoverable fossil fuels form a reservoir that was relatively inactive in the carbon cycle before people began mining and burning fossil fuels. Reservoir sizes are expressed in gigatons of carbon.

of new production was thought to be approximately 3.4 gigatons per year (Koblentz-Mishke, Volkovinsky and Kabanova 1970). But many investigators now believe that sampling and incubation procedures used in estimating ocean production have inhibited the growth of phytoplankton, resulting in a systematic underestimate of oceanic production. Recent measurements that eliminate this inhibition indicate that new production may be as much as 8.3 gigatons per year, or 2.4 times as large as the estimates derived from the work of Koblentz-Mishke and her colleagues. The lack of agreement among oceanographers about these revisions adds uncertainty to our understanding of this important flux in the global carbon cycle.

Special attention has been directed to the important role of polar oceans in biological pumping; moreover, the polar seas offer us a glimpse of ocean activity under extreme climatic conditions. In upwelling areas of the Antarctic Ocean, nutrient supplies—with the possible exception of iron—do not limit primary production, as they do in most of the world's oceans. Instead, there are other limiting factors such as reduced incident solar radiation during seasonal extensions of sea ice. This suggests that by reducing the extension of sea ice, warming at high latitudes might enhance biological production and increase the downward flux of carbon.

Recent research has also shaken long-held assumptions about another aspect of the biological transfer of carbon in the oceans. Recently several geochemists using a new technique for the oxidation of organic compounds in seawater (Sugimura and Suzuki 1988) have found a large quantity of dissolved organic compounds, largely carbohydrates and proteins, in the world's oceans. The new estimates of dissolved organic carbon in both surface and deep water are at least twice as large as previously accepted values. These compounds, which are likely produced by photosynthetic organisms at the ocean surface, are transported by advection or mixing rather than by sinking. The presence of such large quantities of newly detected dissolved and actively decomposing organic carbon complicates the interpretation of depth profiles of oxygen and carbon, which are used for making ocean carbon-flux estimates.

There have been some difficulties in reproducing the results of Sugimura and Suzuki, but the measurements made using this method remain striking. Their apparatus, a complete combustion column, can extract large amounts of dissolved organic carbon from water samples from which it was thought all dissolved organic carbon had been removed. If a much larger pool of this carbon exists, and if it has a mean lifetime of 100 years as they suggest, then the mean production rate of dissolved organic carbon would be about 4.3 gigatons per year—comparable to the conventional estimate of new production. The estimated pool of dissolved organic carbon based on the new measurements is probably at least twice the size of either the atmospheric CO_2 pool or the carbon pool represented by terrestrial plants. Its production and dispersal is a potentially significant biologically induced flow of organic matter from the ocean surface to deep water. Small changes in such a pool would appreciably alter the ocean-atmosphere CO_2 exchange rate.

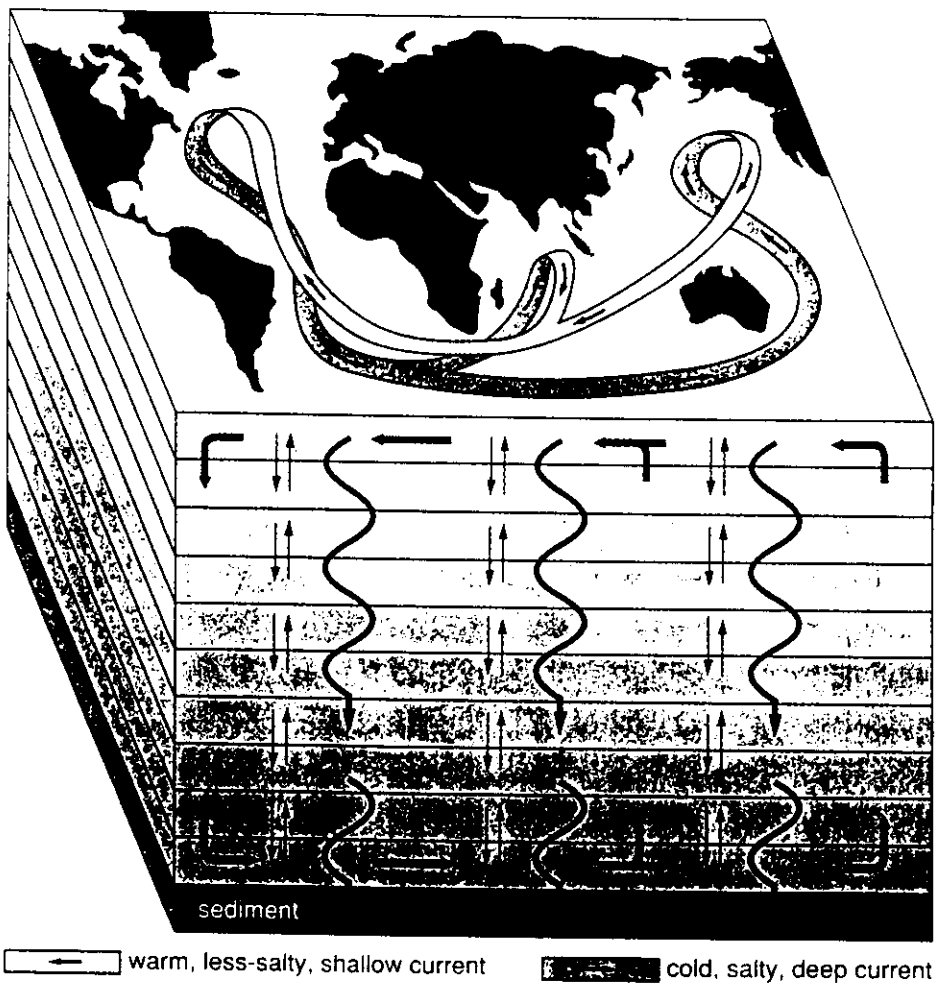
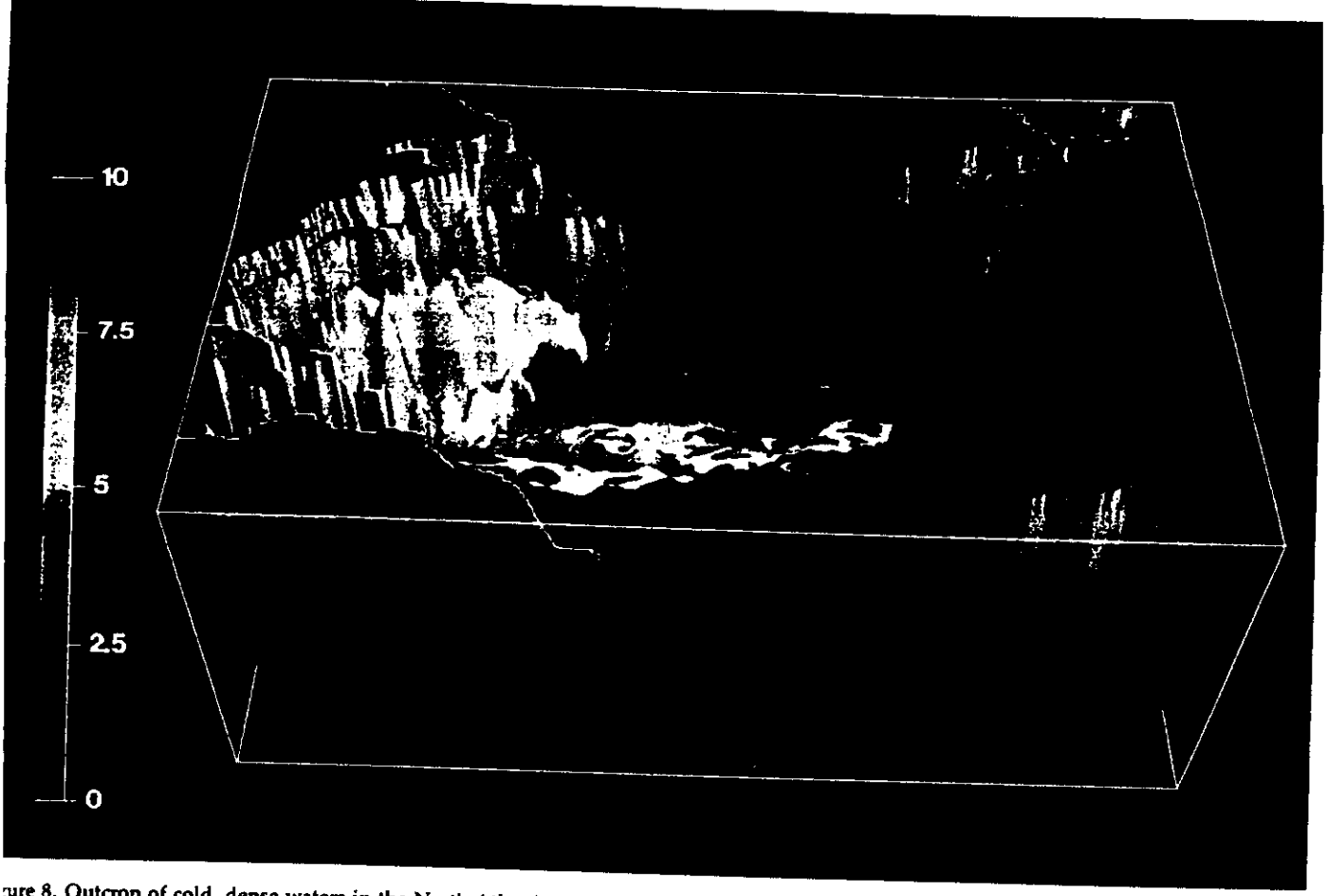


Figure 7. Flows of carbon in the world's oceans can be depicted as movements within and between box-shaped ocean compartments. The blue arrows in this vertical cross section indicate global circulation: upwelling of deep waters in the northern Indian Ocean and equatorial Pacific, downwelling in the North Atlantic. Horizontal transport occurs in both the deep, cold ocean layers and the warm surface waters. Wavy arrows represent biological pumping, which transfers carbon to the deep waters. Diffusion also moves carbon between layers. Model calculations considering these flows, calibrated with measurements of the movements of chemical tracers, suggest that the oceans took up between 26 and 34 percent of the fossil-fuel carbon put into the atmosphere between 1958 and 1980. (After Broecker 1985.)

The Terrestrial Carbon Cycle

Terrestrial carbon dynamics have also presented daunting challenges to those seeking to understand the global carbon cycle. As in marine

7.



ure 8. Outcrop of cold, dense waters in the North Atlantic provides a direct path for atmospheric carbon invading deep ocean water. The tcrop is seen in purple near the top of this three-dimensional image of an isopycnal surface, or equal-density horizon, in the Atlantic. The nputer-generated image, which shows the area between the equator and 55 degrees north, is produced by a model based on principles of an dynamics and forced with seasonally varying wind stress, heating and fresh-water fluxes at the sea surface. Colors show the "age" of ter on the isopycnal surface—the time since it was last exposed to the atmosphere. The vertical dimension of the box indicates the depth—cending from the surface to 500 meters—at which water of this density is found in the ocean. Near the equator, water on this isopycnal not been exposed to the atmosphere for a decade. The model was constructed by Frank O. Bryan and William R. Holland of the National ıter for Atmospheric Research.

logical pumping, the cycle on land gins with primary production by otosynthetic plants that take up rganic carbon as CO_2 and make anic compounds, which serve as source of chemical energy in the d chain. Terrestrial ecosystems re- n carbon to the atmosphere by piration, decay and fires. The ter- rial carbon reservoir is actually a ection of carbon pools with a wide ge of net primary production s, respiration rates and carbon ıover times.

Data from the International Bio- cal Program, an effort to assess ogical productivity worldwide, ame available in the late 1970s. y Olson and his colleagues used information in 1983 in construct- a new global estimate of terres- carbon pools. Their estimate con- red both human influences and ural factors and accounted for periodic disturbances that might cause regional variations from pristine conditions in which ecosystem carbon fluxes are thought to be in balance. In calculating the net uptake of carbon by terrestrial vegetation, Olson distinguished three components of live vegetation: low vegetation, woody parts of trees and nonwoody parts of trees. While the net primary production amounts for the three pools are similar, tree wood and low vegetation are larger pools with slower turnover rates than tree leaves.

The total net primary production of terrestrial vegetation has been estimated at 62 gigatons per year. This is assumed to be approximately balanced, over a period of several years, by an equivalent return of carbon to the atmosphere from decomposition of litter and soil organic matter. The return flow comes from two pools of "dead" organic matter: the detritus/decomposer pool, made up of litter and decomposers at the soil surface, and the active soil carbon pool, which consists of that fraction of the carbon in soils, and the associated decomposer organisms, that are in relatively active exchange with the atmosphere. Figure 10 shows the relationship of these pools to other components of the terrestrial ecosystem.

The global totals do not illustrate the wide variations in the activity of these pools. The rates of input for different ecosystem types, such as temperate forest and tundra, vary over several orders of magnitude. The turnover time of carbon in the detritus/decomposer pool can range from less than a year in moist tropical forests to decades in cold, dry boreal forests. Soil contains both active carbon pools and relatively inactive ones; the activity of soil organic matter varies with depth, soil texture,

8.

climate and the chemistry of the organic matter. For example, the closer the organic matter is to the surface, the more readily decomposed it is, and, therefore, the greater its impact on annual or seasonal CO_2 cycles. Pools that are larger but have lower exchange rates may regulate long-term trends. In addition, some soils, even though undisturbed by human activities, are not currently in a steady state. Globally, peatland and wetland soils may be accumulating 0.1 to 0.3 gigaton of carbon per year, and desert soils may store 0.01 gigaton of carbon per year in the form of carbonates.

The balance between these processes—assimilation by photosynthesis and the release of carbon from both living and dead material—determines the magnitude of the net exchange of carbon between the atmosphere and the world's terrestrial systems. Over time periods shorter than a decade, carbon fluxes may be out of balance at specific locations, shifting with the availability of nutrients, changes in the weather, and sporadic disturbances. But over long periods, for reasonably undisturbed ecosystems, uptake and loss are generally assumed to be in balance, so

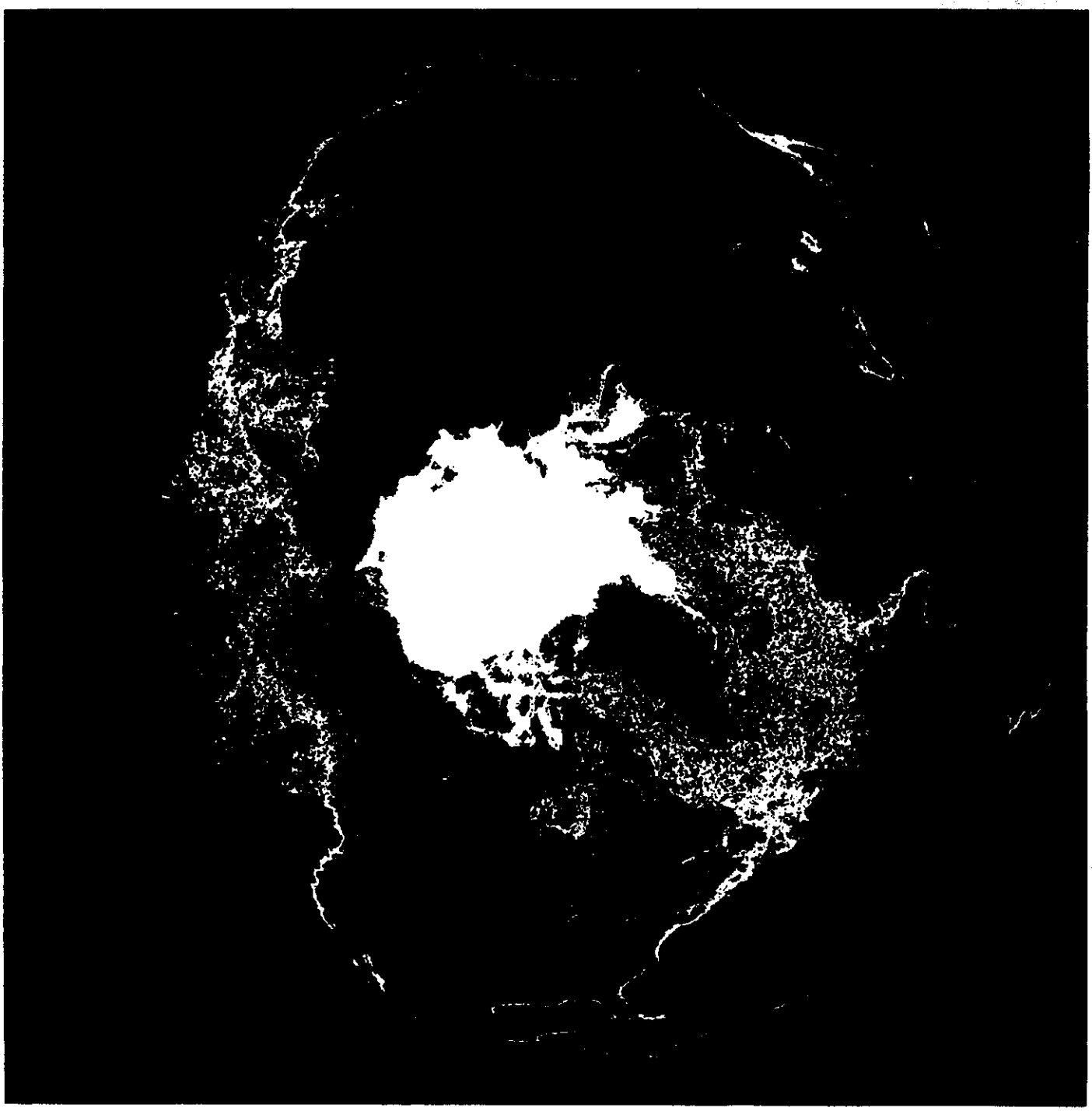


Figure 9. Polar oceans are the sites of abundant biological activity, as shown in these composite images produced by the Coastal Zone Color Scanner, which operated on the *Nimbus*-7 satellite from 1978 to 1986. Phytoplankton blooms in both the Arctic and Antarctic oceans are highly seasonal, limited by the availability of sunlight. The images are based on cumulative radiometric measurements of phytoplankton

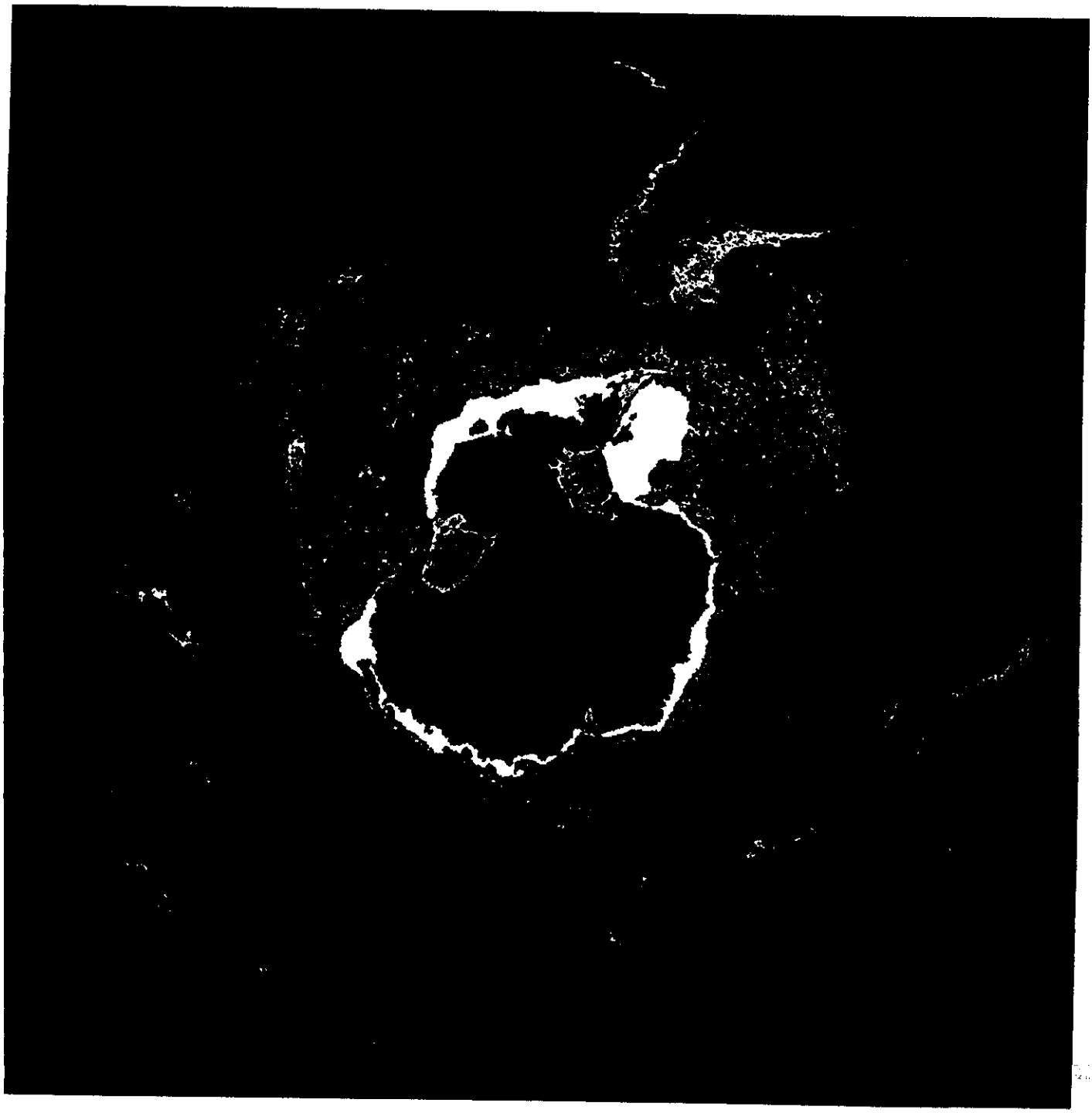
9.

that the average standing crop of carbon reaches a steady-state level.

We shall assume, as do the authors of nearly all studies of human disturbance of vegetation, that the exchange of carbon between the atmosphere and undisturbed terrestrial ecosystems is more or less in balance over annual or decade time scales. Some investigators, notably Ariel Lugo and Sandra Brown (1986), argue that we cannot assume there are enough reasonably undisturbed regions of the terrestrial world for such an assumption to be usefully applied to carbon-cycle calculations. Nevertheless, if care is taken to incorporate some natural disturbances into what we consider to be equilibrium carbon-pool sizes, this assumption provides a basis for estimating the net flux of carbon between the atmosphere and terrestrial systems due to human activities—a flow that has been impossible to measure directly.

Impact of Human Land Use

Several methods have been developed to estimate the recent effect of land use, such as forestry and agriculture, on the net flux of carbon between the atmosphere and the terrestrial ecosystem. One approach,



gment concentrations, an index of photosynthetic activity near the surface. Yellow to red hues indicate the highest concentrations, blues d purples the lowest. Regions where no measurements were taken or where the sensor's view was obscured by clouds are colored gray. nages by Gene Carl Feldman, National Aeronautics and Space Administration Goddard Space Flight Center.)

called reconstruction, relies on data recording changes in land use, from which one can estimate changes in the amount of carbon stored in vegetation and soil. A second approach attempts to deduce the flux from carbon pools on land into the atmosphere through the technique called deconvolution.

During the 1980s several studies attempted to reconstruct the impact of land-use changes on the net release of carbon into the atmosphere. Studies focusing on land clearing for cropping in specific regions produced estimates of the flow of carbon to the atmosphere in the range from 0.4 to 2.6 gigatons for 1980. Almost all of this amount came from the tropics; the analyses lacked comprehensive treatments of the impacts of fire suppression in the Northern Hemisphere (which results in increased carbon storage within extant forests and forest expansion into sparsely wooded areas) or of logging, harvesting of fuel wood, deliberate burning, and grazing in tropical savannas.

Other studies have attempted to reconstruct a time series of the net biotic flux of carbon since 1800 by using land-use data. The most recent estimate (Houghton 1989) reconstructs yearly changes in the amount of carbon in terrestrial systems by considering 10 geographic regions, each with up to 14 types of ecosystems and seven types of land-use changes. The analysis tracks the area, age and carbon content of each disturbed ecosystem, using response curves to describe the change in carbon stocks after a disturbance. It also computes the oxidation of fuel wood and wood products. The reconstruction yields an estimate that the total net flow of carbon to the atmosphere as a result of changes in land use

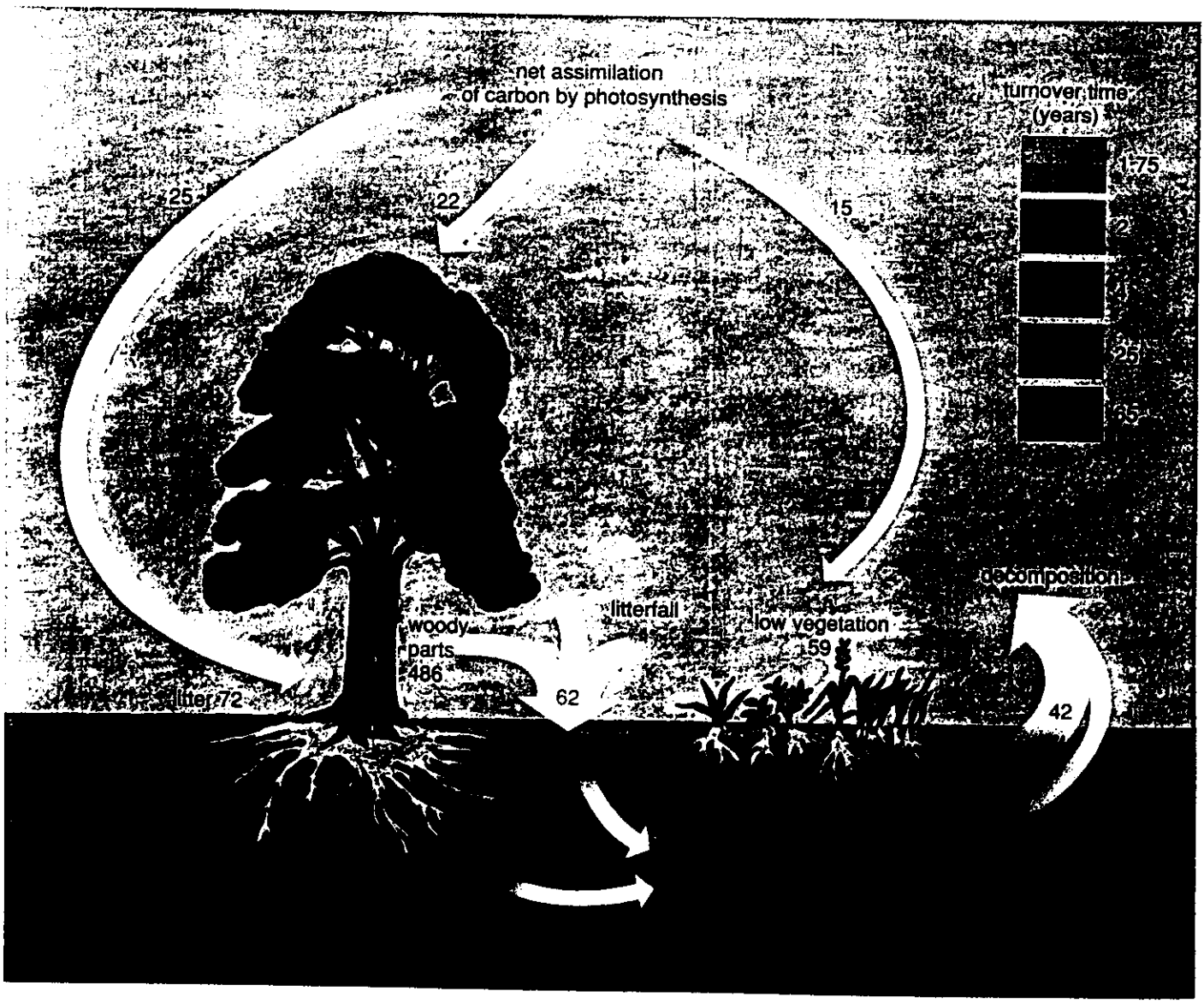


Figure 10. Terrestrial flows of carbon are determined by varying rates of photosynthesis, respiration and decay, and by the turnover times of the carbon reservoirs in the biosphere. Carbon is assimilated from the atmosphere by the woody and nonwoody parts of trees and by ground vegetation such as grasses and low bushes. An estimated 62 gigatons of carbon in plant material falls to the ground as litter or enters the soil by root mortality each year. The carbon contained in litter and soil is returned to the atmosphere through decomposition. While the woody parts of trees represent the largest active reservoir of terrestrial carbon, they exhibit very slow turnover; nonwoody tree parts store less carbon but turn over rapidly. As a result, these reservoirs assimilate similar amounts of carbon over time. The illustration represents the flows of carbon within the system and sizes of terrestrial carbon compartments in gigatons.

/een 1800 and 1980 amounted to /een 90 and 120 gigatons.

But the estimates derived by the nstruction approach are inconsis- with the observed increase in)spheric carbon. If the estimated se of carbon due to changes in use (90 to 120 gigatons) is added ecorded releases from burning l fuels (150 to 190 gigatons), and timated ocean uptake (40 to 78 ons) is subtracted, the increase mospheric carbon for the period 1800 to 1980 should, using the mes, lie in the range from 162 to gigatons. The observed increase proximately 150 gigatons—be- the minimum calculated using reconstruction estimates. Since anges of predicted and observed ases in atmospheric carbon do ven overlap, many scientists re- skeptical that we can analyze mpact of fossil-fuel burning on lobal carbon cycle.

Because changes in terrestrial n pools are difficult to measure, often assumed that reconstruc- of the terrestrial flux is in error. may or may not be correct, but it work suggests several possible es of error in the reconstruc- . The amount of carbon in initial, sturbed ecosystems may have overestimated, so that projec- of the amount released by ges in land use were too high. ven larger problem may lie in implifying assumption that hu- influences on many ecosystems negligible before land-use con- n. Carbon stocks may have gradually lowered over long pe- before land areas were com- y converted to crops or shifting ation.

An alternative method for esti- g the land-use flux of carbon is nvolution. The essential idea is btract fossil-fuel emissions from ured changes in atmospheric n, making allowances for the e of carbon by the oceans; the ence should be the contribution e terrestrial system. Given our nption of carbon balance in nat- ystems, this flux is equivalent to rom land-use changes.

Deconvolution studies have pro- l a wide spectrum of results. es done in the early 1980s used urements of ^{13}C in tree rings to ate atmospheric carbon levels in the period before the Mauna Loa record begins. However, local environmental conditions influence the relationship between ^{13}C in tree rings and atmospheric CO_2 levels, complicating this method. Analysis of bubbles trapped in ancient glacial ice now provides a direct means of measuring historical levels of ^{13}C and CO_2 partial pressure. Depending on which ocean model is employed, deconvolution based on the ice-core record gives a cumulative release of from 90 to 150 gigatons of carbon from 1800 to 1980.

The deconvolution estimates suggest a historical pattern that does not agree with the pattern derived from historical reconstruction. Figure 13 compares the results of studies done by the two techniques. The reconstruction estimate shows an exponential increase in carbon release since 1900, due largely to the increased rate of tropical-forest clearing over the past 50 years. The deconvolution estimate suggests a steadily declining land-use flux, making the terrestrial system a CO_2 source in the 19th century and a sink in the latter part of the 20th century. This lack of apparent increase demands some explanation, given the vast scale on which tropical forests are being destroyed today. One line of speculation suggests there was substantial land clearing in the northern temperate zones in the 19th century, and much of this area may now be serving as a CO_2 sink. Analyses of key regions indicate, however, that vegetation regrowth is unlikely to be large enough to account for most of the discrepancies.

Figure 11. Soil carbonate, or caliche, serves as a carbon reservoir in dry ecosystems, forming at a global rate of about 0.01 gigaton per year. Caliche in the desert landscape of La Mesa, near Las Cruces, New Mexico, is clearly visible as a white layer in the soil profile. (Photograph by William H. Schlesinger, Duke University.)

If the reconstruction method turns out to be correct, attention will focus on adjustments to the ocean models as a means of achieving consistency. Could any conventional ocean model reconcile the estimated rate of land-use release with the Mauna Loa and ice-core measurements? Ian Enting and J. V. Mansbridge (1987), using a linear-programming technique to answer this question, concluded that the discrepancy is too large. They mention four possible remedies, one of which is particularly worthy of notice here: the possibility of nonlinear effects in the uptake of CO_2 by the oceans. This notion is strengthened by other lines of evidence suggesting that the complex dynamics of the global circula-

January–February

Figure 12. Carbon stores in the terrestrial ecosystem are dispersed unevenly around the globe. These images show plant activity during two-month periods in 1987 using the Global Vegetation Index, which is compiled with data from sensors mounted on National Oceanic and Atmospheric Administration satellites. The images show the cycles of photosynthetic activity in the Northern and Southern hemispheres.

tion of ocean waters are important in describing CO_2 uptake. Such considerations are leading to the development of three-dimensional general-circulation models of the oceans, which can accommodate nonlinear effects.

Much of the progress in understanding the global carbon cycle has been accomplished by a divide-and-conquer strategy, in which scientists from many disciplines work separately on separate pieces of the problem. Although this approach will continue to refine our knowledge of the global carbon cycle, the pieces do not always fit together. Over the past decade, a new perspective has emerged. This approach recognizes that the oceans, terrestrial ecosystems, the atmosphere and climate form an interconnected system that can be studied in its entirety. Components of this global system interact through the hydrologic cycle of evaporation and precipitation, through the flow of carbon and nutrients in food chains, and through biological and geochemical reactions that result in trace-gas exchanges. All of these phenomena in turn have an influence on climatic conditions at the earth's surface. It is just such feedback relations—where the output of a system affects its own input—that give rise to complex responses.

Three kinds of research are important to this approach: global modeling, which couples system components that were previously considered separately; spatial studies, which explore regional differences in carbon exchanges; and the analysis of temporal patterns of CO_2 variation in the atmosphere.

Global System Modeling

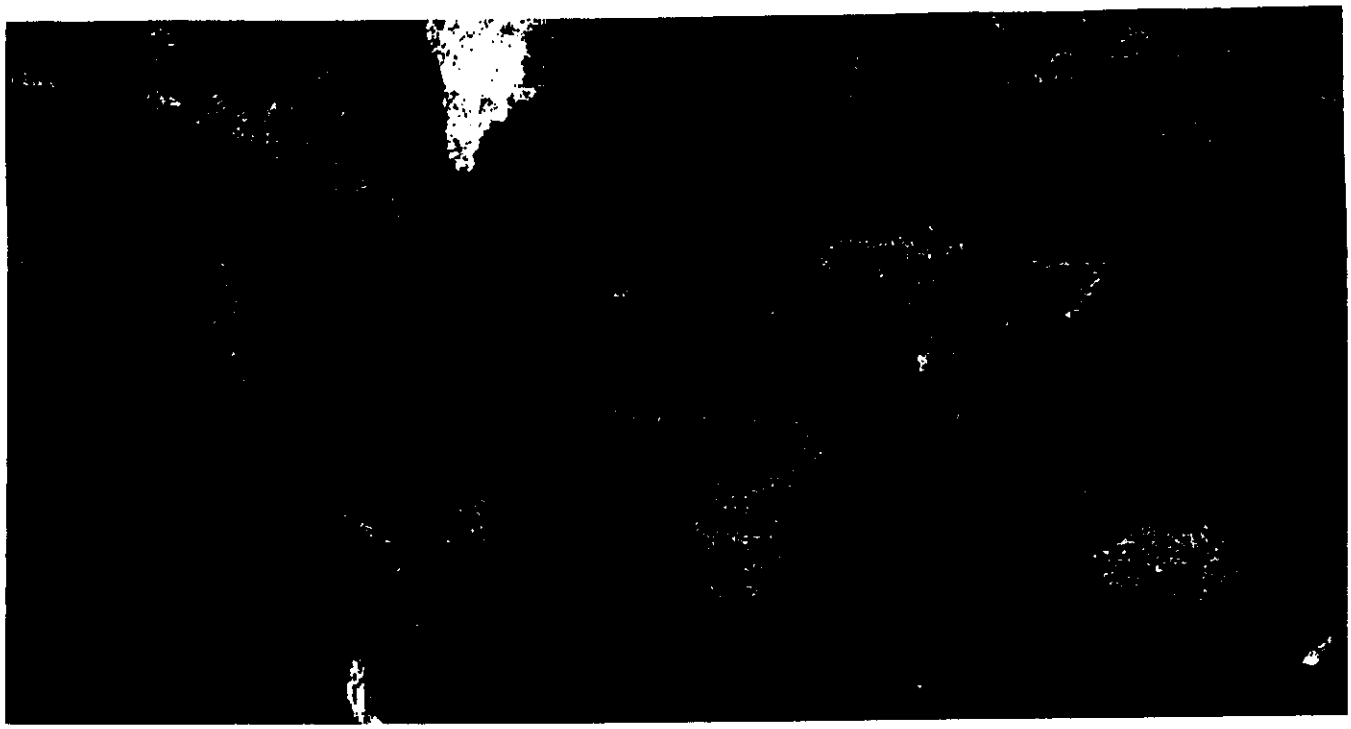
Mathematical models of carbon flow between the oceans and the atmosphere and between terrestrial ecosystems and the atmosphere have long been useful tools in carbon-cycle research. In the area of ocean-atmosphere dynamics, recent models have improved our understanding by incorporating three spatial dimensions and by allowing for the simultaneous transfer of heat and carbon, thus coupling the biogeochemical system with the climate system.

One step in this direction is the lateral-transport model of the global oceans proposed by Wallace Broecker and his colleagues in 1985. The model divides the Atlantic and Pacific oceans into five latitudinal zones and the Indian Ocean into three latitudinal zones. It incorporates upwelling coupled with a divergence of surface waters in the tropics, the Antarctic regions and the North Pacific. A corresponding convergence of surface-water flow coupled with downwelling is necessary in the temperate regions of all the oceans and in the North Atlantic.

In Broecker's model the oceans can take up 35 percent of the CO_2 released from fossil-fuel burning during the period from 1958 to 1980—slightly more than traditional globally averaged models suggest. Oceanographers have hoped to build more complex ocean models that would help balance the global carbon cycle, but preliminary results do not show significant increases in carbon uptake from these models. Still more detail could be included in models based on real-world measurements of temperature, salinity and currents, and on data describing the distribution of tracers in the sea. More work is needed to ascertain that the ocean-circulation models describe the ocean adequately and to include biological processes.

General-circulation models of the atmosphere have been coupled with similar models of fluid and heat transport in the oceans to understand the exchange of heat and moisture

13.



August

green represents the highest "greenness index." Yellow indicates moderate vegetation, and browns and grays show minimal activity. alues were omitted for the areas in white because of cloud cover and other technical problems. (Images courtesy of Kevin P. Gallo, /National Environmental Satellite, Data, and Information Service, and the U.S. Geological Survey/EROS Data Center.)

:en the oceans and atmosphere. a convergence of efforts is g models of atmospheric and ic circulation, and incorporat- rbon exchanges and flows into :ean models. This combined ap- h promises to be a powerful tool veloping an understanding of :omplex relationship between biogeochemistry and climate mics.

Carbon-cycle models that at- t to describe terrestrial processes ntly do not include a central e of the dynamics of the sys- -the dependence of its major sses on environmental condi- such as temperature, moisture CO_2 concentration. All ecological sses are sensitive to tempera- and moisture. These environ- al conditions control the faster- nding biological processes of rbon cycle: photosynthesis, res- on, translocation and transpira- in plants, and the turnover of bial decomposers. Photosyn- s and respiration also can be ed by increases in atmospheric Such fast responses are con- ed by slow ecosystem dynamics allocate carbon to various com- nents (leaves and fine roots, d, litter and soil organic matter), decompose dead organic matter and alter ecosystem composition through replacement of plant species.

Feedback mechanisms (in which CO_2 emissions lead indirectly to greater carbon uptake) could produce changes in terrestrial production large enough to compensate, at least in part, for decreased production and storage caused by human land use. This could, in turn, account for some or all of the inconsistencies in historical reconstructions of carbon flows. But in order to describe realistically how terrestrial carbon dynamics respond to varying environmental factors, two classes of terrestrial models must be merged: physiological models of the fast carbon dynamics and ecosystem models of the slow carbon dynamics. This is not a simple matter. Models of fast processes are designed for small time intervals and small spatial extents—hours and centimeters. Because of nonlinearities and complex spatial variations, the models cannot simply be integrated to take in a larger scope. Furthermore, computational errors grow unacceptably when small deviations accumulate over long periods.

Another significant challenge is the wide variation of environmental conditions across the earth's surface. Global-scale analyses of carbon dynamics that take into account the spatial distribution of terrestrial biological and environmental factors have only recently been attempted. These models offer provocative results. For example, Gerd Esser (1987) incorporates a terrestrial CO_2 "fertilization" response function that, in his simulation, increases net primary production by about 5 gigatons per year by 1980. In the model, the additional production stimulated by excess atmospheric CO_2 over the period from 1860 to 1980 is responsible for an additional terrestrial uptake of 73 gigatons of carbon, offsetting a significant portion of the impact of land clearing during the same period.

It is not yet possible to independently evaluate the results of such models by direct observations. A promising direction in global modeling is offered by model formulations that would simulate certain observable variations in the global system, such as the seasonal and latitudinal variation of CO_2 and ^{13}C in the atmosphere.

Spatial and Seasonal Patterns

The spatial distribution of CO_2 sources and sinks is an important area of study. Annual mean atmo-

14.

spheric concentrations of CO_2 vary continuously with latitude and are higher at the North Pole than at the South Pole. It is thought that this gradient is maintained by the geographical distribution of sources and sinks in the oceans and on land, coupled with atmospheric mixing. The fact is, however, very little is known about this distribution.

Recently, some information on the distribution of sea-surface CO_2 concentrations has been compiled. These studies locate sources of CO_2 in the equatorial Pacific and Atlantic, the northwestern Pacific and the northwestern Indian oceans, where there is upwelling of deep waters. The subantarctic Southern Ocean and the northern North Atlantic Ocean are sinks of CO_2, with low surface concentration. To incorporate these geographic variations into a model of the global carbon cycle, we need to know the exchange rate across the air-water interface, which depends not only on CO_2 concentration but also on temperature and wind speed. Given data on these quantities, the spatial information yields an estimate of the global uptake of CO_2 by the ocean. An estimate made by Pieter Tans, Inez Fung and Taro Takahashi (1990) using this method is 1.6 gigatons per year, considerably lower than estimates obtained by other methods. Sensors aboard future satellites should improve these estimates by mapping sea-surface roughness (an indicator of wind speed) and color (an indicator of chlorophyll or phytoplankton concentration). The satellite observations in turn will need to be calibrated with ground-truth experiments.

During the past decade it has become clear that estimates of regional and global terrestrial carbon dynamics must also take into account their variability across space and time. Currently, our knowledge of carbon dynamics involving vegetation is limited to fairly simple extrapolations of measurements made in relatively small plots. Even if such measurements could be made exactly, they would fail to account for year-to-year variations in climate, or the effects of longer-term disturbances and successional changes.

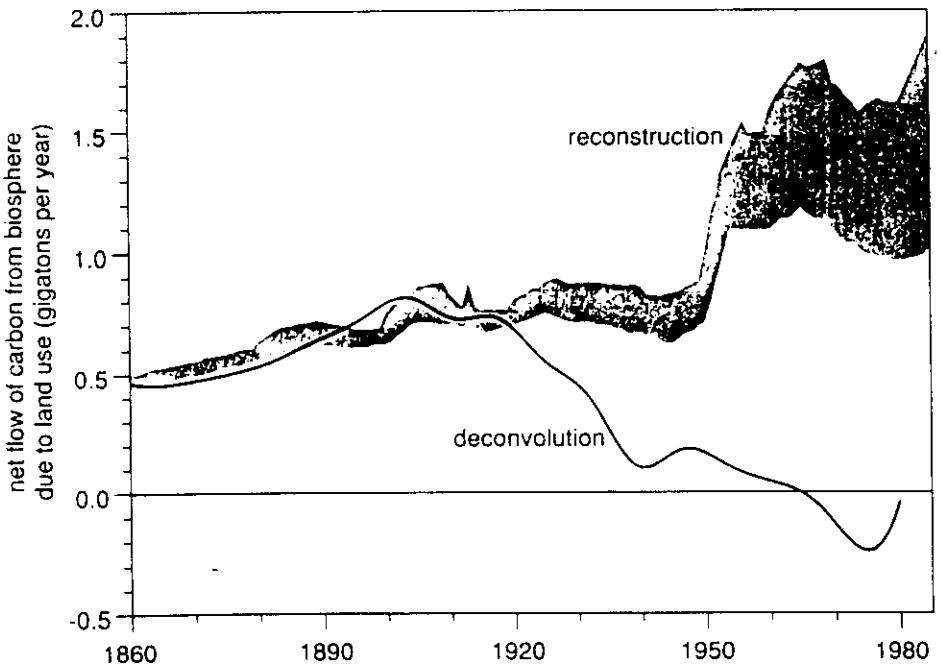


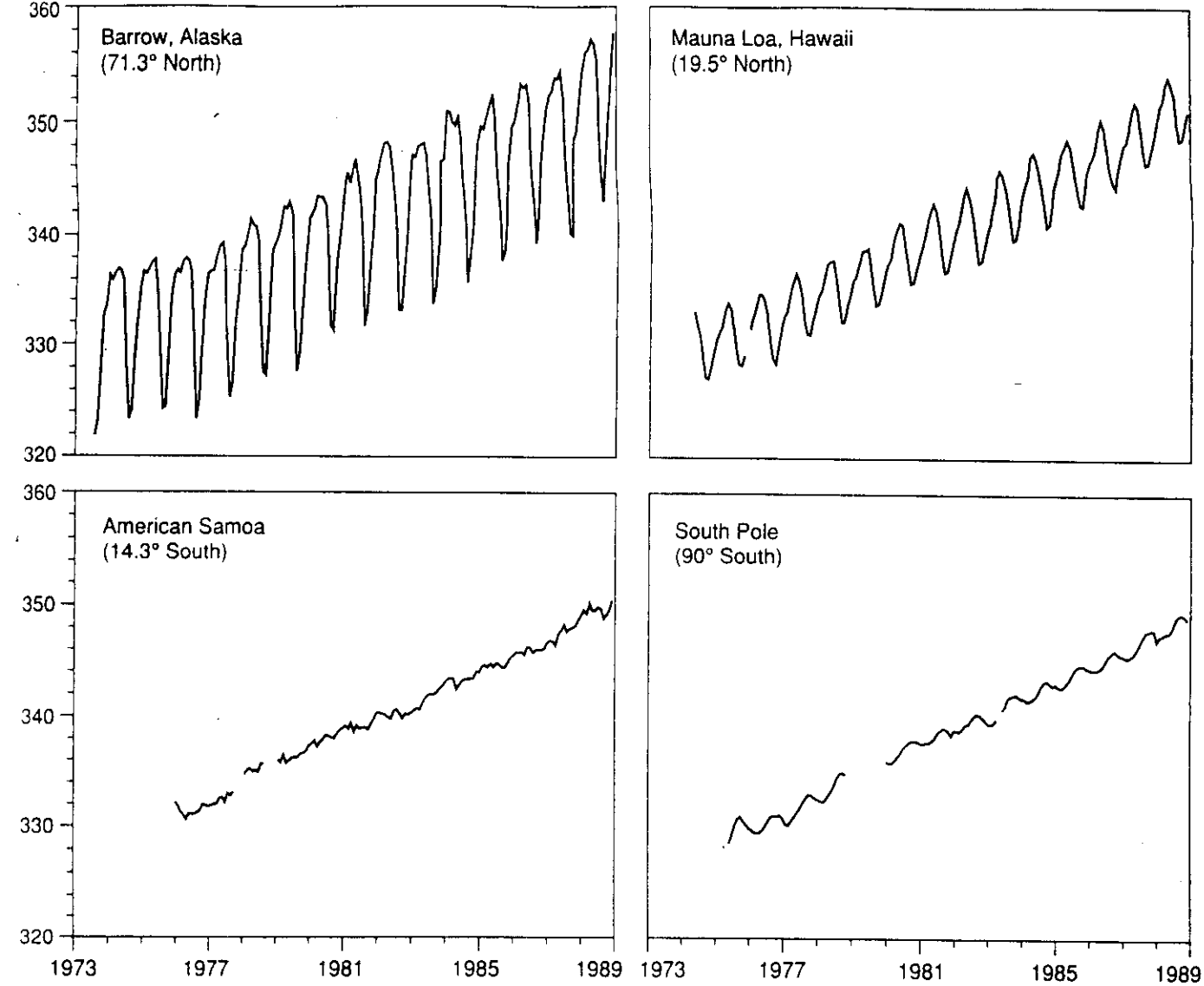
Figure 13. Impact of human land use on the global carbon cycle has proved difficult to estimate. This graph compares the results of recent studies using the techniques of historical reconstruction and deconvolution. The reconstruction study (Houghton 1989) used historical records to calculate changes produced by disturbances of vegetation and soil since 1860. The results are shown as a range of values between high and low estimates. The dramatic increase since 1950 is caused primarily by tropical deforestation. The deconvolution method works differently: it estimates the effect of fossil-fuel emissions and ocean uptake on changes in atmospheric CO_2, then infers that any carbon flows not accounted for must represent the effects of human land use. This method produces a different historical profile, as illustrated by results from a deconvolution study based on a box-diffusion model of ocean uptake and on Siple ice-core and Mauna Loa CO_2 measurements (Siegenthaler and Oeschger 1987).

Moreover, extrapolating from a few acres to an entire continent has obvious hazards. In tropical regions, where most attention has been focused lately, it is now clear that even the most recent estimates of the standing stock of carbon in vegetation—and perhaps estimates of net primary production as well—are too large and should be revised. This may also be true for other regions of the world.

Several global maps of contemporary terrestrial ecosystems have been constructed, an exercise that can serve as a basis for integrating detailed regional information to make global estimates. There is also much promise in using satellite imagery for assessing current patterns of vegetation and land-use, and for determining exchanges of energy, water and CO_2 between the terrestrial surface and the atmosphere. Problems exist, however, in interpreting remotely sensed images in terms of carbon concentrations and land-use change. So far, the interpretation has been done only for selected areas. Possible approaches include the use of remote sensing to classify vegetation cover, to relate observed seasonal photosynthetic activity to atmospheric CO_2 concentration and to monitor changes in productivity and, therefore, in terrestrial carbon storage.

Another important modeling issue is raised by seasonal and year-to-year fluctuations in atmospheric CO_2 levels. Annual variations, which are very small at the South Pole, are strong and regular in the Northern Hemisphere, reflecting the seasonal exchange between the atmosphere and the terrestrial ecosystems (Figure 14). Atmospheric CO_2 measurements show significant growth in the amplitude of this seasonal cycle. At Mauna Loa the annual fluctuation in atmospheric CO_2 grew from 5.5 to 6.4 microliters per liter from 1958 to 1981, a mean rate of increase of 0.66 percent per year. Other records over the past decade exhibit growth rates of from 1 to 2 percent per year.

An increasing amplitude in the seasonal oscillation in CO_2 concentration indicates increased plant activity, but not necessarily increased net carbon storage. The seasonality of fossil-fuel use is insufficient to account for the increase; a more likely explanation lies in the strong temperature dependence of CO_2 respiration from



ure 14. Seasonal cycles of atmospheric CO_2 concentrations are illustrated by measurements from four monitoring stations where the tional Oceanic and Atmospheric Administration takes continuous readings. Analysis of the measurements shows that seasonal cycles in Northern Hemisphere—which reflect the dominance of photosynthesis in the summer and plant respiration in the winter—seem to be reasing in amplitude. This may be a result of global warming. The dots represent monthly averages. The data are from Peterson et al. 6; Komhyr et al. 1989; Thoning, Tans and Komhyr 1989; Waterman et al. 1989; and Gillette et al. 1987.

ints and soils and the observed rming trend over the past decade the Northern Hemisphere.

derstanding Carbon Dynamics

e challenge of future carbon-cycle search is to understand relation-ips among the components of the bal biogeochemical-climate sys-n. Our inability to balance all of the bon fluxes over the period from 00 to the present may result from erlooking a dynamic response of restrial vegetation and ocean pro-sses to changes in environmental nditions. The unexplained re-onse—whose magnitude is be-een +0.5 and –2 gigatons an-ually, depending on various as-mptions—represents about 4 per-cent of net primary production in the terrestrial system, or about 3 percent of the exchange between the ocean and the atmosphere. Current methods do not provide a way to detect the changes in carbon storage that would accommodate such small net fluxes. For the purposes of understanding the carbon cycle and predicting future atmospheric levels of CO_2, therefore, it is essential that we understand how terrestrial vegetation and ocean processes respond to changes in CO_2 and climate. Integrative research tools are now being developed to directly determine the responses of these natural systems over short time scales. In the area of ocean dynamics, additional data and more comprehensive models are needed to link the climatic effects of the atmosphere-ocean system to geochemical events.

In years to come there will likely be shifts in carbon storage by terrestrial ecosystems as small shifts in climate cause imbalances from year to year between production and decomposition-respiration. Observing these shifts may help to determine the magnitude of the terrestrial response. Useful techniques will include remote-sensing measurements of productivity changes as well as carbon-isotope and CO_2 measurements. These, too, need further development and must be interpreted by coupled and geographically explicit process models. Geographically oriented tools also will be important to

16.

understanding the spatial distribution of terrestrial ecosystems in relation to the heterogeneity of climate changes and geological constraints.

Much has been learned in the past decade about the global carbon cycle and how its complexities control CO_2 levels in the atmosphere. The greatest lesson is how dynamic and interactive are the components of the global biogeochemical-climate system.

References

Baes, C. F., H. E. Goeller, J. S. Olson and R. M. Rotty. 1977. Carbon dioxide and climate: The uncontrolled experiment. *American Scientist* 65:310–320.

Barnola, J. M., D. Raynaud, Y. S. Korotkevich and C. Lorius. 1987. Vostok ice core provides 160,000-year record of atmospheric CO_2. *Nature* 329:408–414.

Bolin, B. 1986. How much CO_2 will remain in the atmosphere? In *The Greenhouse Effect, Climatic Change, and Ecosystems*, ed. B. Bolin, B. R. Döös and J. Jäger, pp. 93–155. SCOPE 29. John Wiley, Chichester.

Broecker, W. S., T.-H. Peng, G. Östlund and M. Stuiver. 1985. The distribution of bomb radiocarbon in the ocean. *Journal of Geophysical Research* 90:6953–6970.

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.

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

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

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

Fung, I. Y, C. J. Tucker and K. C. Prentice. 1987. Application of advanced very high resolution radiometer vegetation index to study atmosphere-biosphere exchange of CO_2. *Journal of Geophysical Research* 92:2999–3015.

Gillette, D. A., W. D. Komhyr, L. S. Waterman, L. P. Steele and R. H. Gammon. 1987. The NOAA/GMCC continuous record at the South Pole, 1975–1982. *Journal of Geophysical Research* 92:4231–4240.

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

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 CO_2 to the atmosphere. *Ecological Monographs* 53: 235–262.

Keeling, C. D., R. B. Bacastow, A. F. Carter, S. C. Piper, T. P. Whorf, M. Heimann, W. G. Mook and H. Roeloffzen. 1989. A three-dimensional model of atmospheric CO_2 transport based on observed winds: 1. Analysis of observational data. In *Geophysical Monograph 55*, ed. D. H. Peterson. American Geophysical Union, Washington, D.C.

Koblentz-Mishke, O. I., V. V. Volkovinsky and J. G. Kabanova. 1970. Plankton primary production of the world oceans. In *Scientific Exploration of the South Pacific*, ed. W. Wooster, pp. 183–193. National Academy of Sciences, Washington, D.C.

Komhyr, W. D., T. B. Harris, L. S. Waterman, J. F. S. Chin and K. W. Thoning. 1989. Atmospheric carbon dioxide at Mauna Loa Observatory: 1. NOAA/GMCC measurements with a nondispersive infrared analyzer, 1974–1985. *Journal of Geophysical Research* 94:8533–8547.

Lugo, A.E., and S. Brown. 1986. Steady state terrestrial ecosystems and the global carbon cycle. *Vegetatio* 68:83–90.

Marland, G., T. A. Boden, R. C. Griffin, S. F. Huang, P. Kanciruk and T. R. Nelson. 1989. *Estimates of CO_2 Emissions from Fossil Fuel Burning and Cement Manufacturing, Based on the United Nations Energy Statistics and the U. S. Bureau of Mines Cement Manufacturing Data*. ORNL/CDIAC-25. Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Mopper, K., and E.T. Degens. 1979. Organic carbon in the ocean: Nature and cycling. In *The Global Carbon Cycle*, ed. B. Bolin, E. T. Degens, S. Kempe and P. Ketner, pp. 293–316. SCOPE 13. John Wiley and Sons, New York.

Neftel, A., H. Oeschger, J. Schwander, B. Stauffer and R. Zumbrunn. 1982. Ice core sample measurements give atmospheric CO_2 content during the past 40,000 yr. *Nature* 295:220–223.

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

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.

Peterson, J. P., W. D. Komhyr, L. S. Waterman, R. H. Gammon, K. W. Thoning and T. J. Conway. 1986. Atmospheric CO_2 variations at Barrow, Alaska, 1973–1982. *Journal of Geophysical Research* 88:3599–3608.

Revelle, R., and H. Suess. 1957. Carbon dioxide exchange between atmosphere and ocean and the question of an increase of atmospheric CO_2 during the past decades. *Tellus* 9:18–27.

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., H. Friedli, H. Loetscher, E. Moor, A. Neftel, H. Oeschger and B. Stauffer. 1988. Stable-isotope ratios and concentrations of CO_2 in air from polar ice cores. *Annals of Glaciology* 10:1–6.

Sugimura, Y., and Y. Suzuki. 1988. A high temperature catalytic oxidation method for determination of non-volatile dissolved organic carbon in seawater by direct injection of liquid sample. *Marine Chemistry* 24:105–131.

Takahashi, T., W. S. Broecker, S. R. Werner and A. E. Bainbridge. 1980. Carbonate chemistry of the surface waters of the world oceans. In *Isotope Marine Chemistry*.

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

Thoning, K. W., P. P. Tans and W. D. Komhyr. 1989. Atmospheric carbon dioxide at Mauna Loa Observatory: 2. Analysis of the NOAA/GMCC data 1974–1985. *Journal of Geophysical Research* 94:8549–8565.

Waterman, L. S., D. W. Nelson, W. D. Komhyr, T. B. Harris, K. W. Thoning and P. P. Tans. 1989. Atmospheric carbon dioxide measurements at Cape Matatula, American Samoa, 1976–1987. *Journal of Geophysical Research* 94:14817-14829.

CHAOS: THE CARTOON

17.