Chapter 2. The Carbon Cycle of North America in a Global Context

Coordinating Lead Author: Christopher B. Field[1]

Lead Authors: Jorge Sarmiento[2] and Burke Hales[3]

[1]Carnegie Institution, [2]Princeton University, [3]Oregon State University

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KEY FINDINGS

- Human activity over the last two centuries, including combustion of fossil fuel and clearing of forests, has led to a dramatic increase in the concentration of atmospheric carbon dioxide. Global atmospheric CO_2 concentrations have risen by 31% since 1850, and they are now higher than they have been for 420,000 years.
- North America is responsible for approximately 27% of the emissions produced globally by fossil-fuel combustion, with the United States accounting for 86% of the North American total.
- Anthropogenic emissions (a carbon source) dominate the carbon budget of North America. Largely unmanaged, unintentional processes lead to a smaller carbon sink (uptake of carbon). The sink is approximately 30% of the North American emissions, 9% of global emissions, and approximately 50% of the global terrestrial sink inferred from global budget analyses and atmospheric inversions.
- While the future trajectory of carbon sinks in North America is uncertain (substantial climate change could convert current sinks into sources), it is clear that the carbon cycle of the next few decades will be dominated by the large sources from fossil-fuel emissions.
- Because North American carbon emissions are at least a quarter of global emissions, a reduction in North American emissions would have global consequences.

THE GLOBAL CYCLE

The modern global carbon cycle is a collection of many different kinds of processes, with diverse drivers and dynamics, that transfer carbon among major pools in rocks, fossil fuels, the atmosphere, the oceans, and plants and soils on land (Sabine *et al*., 2004b) (Fig. 2-1). During the last two centuries, human actions, especially the combustion of fossil fuel and the clearing of forests, have altered the global carbon cycle in important ways. Specifically, these actions have led to a rapid, dramatic increase in the concentration of carbon dioxide (CO_2) in the atmosphere (Fig. 2-2), changing the radiation balance of the Earth (Hansen *et al*., 2005), and most likely warming the planet (Mitchell *et al*., 2001). The cause of the recent increase in atmospheric CO_2 is confirmed beyond a reasonable doubt (Prentice, 2001). This does not imply, however, that the other components of the carbon cycle have remained unchanged during this period. The background or unmanaged parts of the carbon cycle have, in fact, changed dramatically over the past two centuries. The consequence of these changes is that only about 40% ± 15% of the carbon dioxide emitted to the atmosphere from fossil-fuel combustion and forest clearing has remained there (with most of the uncertainty in this number due to the uncertainty in carbon lost from forest clearing) (Sabine *et al.*, 2004b). In essence, human actions have received a large subsidy from the unmanaged parts of the carbon cycle. This subsidy has sequestered, or hidden from the atmosphere, approximately 279 ± 160 Gt of carbon. [Throughout this chapter, we will present the pools and fluxes in the carbon cycle in Gt C (1 Gt = 1 billion tons or 1×10^{15} g). The mass of CO_2 is greater than the mass of carbon by the ratio of their molecular weights, 44/12 or 3.67 times; 1 km^3 of coal contains approximately 1 Gt C.]

Figure 2-1. Schematic representation of the components of the global carbon cycle. The three panels show (A) the overall cycle, (B) the details of the ocean cycle, and (C), and the details of the land cycle. For all panels, carbon stocks are in brackets, and fluxes have no brackets. Pre-anthropogenic stocks and fluxes are in black. Anthropogenic perturbations are in red. For stocks, the anthropogenic perturbations are the cumulative total since 1850. Anthropogenic fluxes are means for the 1990s. Redrawn from (Sabine *et al*., 2004b) with updates as discussed in the text.

Figure 2-2. Atmospheric CO_2 concentration from 1850 to 2005. The data prior to 1957 (red circles) are from the Siple ice core (Friedli *et al*., 1986). The data since 1957 (blue circles) are from continuous atmospheric sampling at the Mauna Loa Observatory (Hawaii) (Keeling *et al*., 1976;, Thoning *et al*., 1989) (with updates available at http://cdiac.ornl.gov/trends/co2/sio-mlo.htm).

The recent subsidy or sequestration of carbon by the unmanaged parts of the carbon cycle makes them critical for an accurate understanding of climate change. Future increases in carbon uptake in the unmanaged parts of the cycle could moderate the risks from climate change, while decreases or transitions from uptake to release could amplify the risks, perhaps dramatically.

In addition to its role in the climate, the carbon cycle intersects with a number of critical earth system processes. Because plant growth is essentially the removal of carbon dioxide from the air through photosynthesis, agriculture and forestry contribute important fluxes. Wildfire is a major release of carbon from plants and soils to the atmosphere (Sabine *et al*., 2004b). The increasing concentration of CO_2 in the atmosphere has already made the world's oceans more acid (Caldeira and Wickett, 2003). Future changes could dramatically alter the composition of ocean ecosystems (Feely *et al*., 2004; Orr *et al*., 2005).

The Unmanaged Global Carbon Cycle

The modern background, or unmanaged, carbon cycle includes the processes that occur in the absence of human actions. These processes are, however, currently so altered by human influences on the carbon cycle that it is not appropriate to label them natural. This background part of the carbon cycle is dominated by two pairs of gigantic fluxes with annual uptake and release that are close to balanced (Sabine *et al.*, 2004b) (Fig. 2-1). The first of these comprises the terrestrial carbon cycle: plant growth on land annually fixes about 57 ± 9 Gt of atmospheric carbon, approximately ten times the annual emission from fossil-fuel combustion, into carbohydrates. Respiration by land plants, animals, and microorganisms, which provides the energy for growth, activity, and reproduction, returns a slightly smaller amount to the atmosphere. Part of the difference between photosynthesis and respiration is burned in wildfires, and part is stored as plant biomass or soil organic carbon. The second comprises the ocean carbon cycle: about 92 Gt of atmospheric carbon dissolves annually in the oceans, and about 90 Gt yr^{-1} moves from the oceans to the atmosphere (While the gross fluxes have a substantial uncertainty, the difference is known to within ± 0.3 Gt) . These air-sea fluxes are driven by internal cycling within the oceans that governs exchanges between pools of dissolved CO_2, bicarbonate (HCO_3^-), and carbonate ($CO_3^=$); organic matter; and calcium carbonate.

Before the beginning of the industrial revolution, carbon uptake and release through these two pairs of large fluxes were almost balanced, with carbon uptake on land of approximately 0.55 ± 0.15 Gt C yr^{-1} transferred to the oceans by rivers and released from the oceans to the atmosphere. As a consequence, the level of carbon dioxide in the atmosphere varied by less than 25 ppm in the 10,000 years prior to 1850 (Joos and Prentice, 2004). But atmospheric CO_2 was not always so stable. During the preceding 420,000 years, atmospheric CO_2 was 180–200 ppm during ice ages and approximately 275 ppm during interglacials (Petit *et al.*, 1999). The lower ice-age concentrations in the atmosphere most likely reflect a transfer of carbon from the atmosphere to the oceans, possibly driven by changes in ocean circulation and sea-ice cover (Sigman and Boyle, 2000; Keeling and Stephens, 2001). Enhanced biological activity in the oceans, stimulated by increased delivery of iron-rich terrestrial dust, may have also contributed to this increased uptake (Martin, 1990).

In the distant past, the global carbon cycle was out of balance in a different way. Fossil fuels are the product of prehistorically sequestered plant growth, especially 354 to 290 million years ago in the Carboniferous period. During this time, luxuriant plant growth and geological activity combined to bury a small fraction of each year's growth. Over millions of years, this gradual burial led to the accumulation of vast stocks of fossil fuel. The total accumulation of fossil fuels is uncertain, but probably in the range of 6000 ± 3000 Gt (Sabine *et al.*, 2004b). It also led to a near doubling of atmospheric oxygen (Falkowski *et al.*, 2005).

Anthropogenic Perturbations

Since the beginning of the industrial revolution, there has been a massive release of carbon from fossil-fuel combustion and deforestation. Cumulative carbon emissions from fossil-fuel combustion, natural gas flaring, and cement manufacture from 1751 through 2003 are 304 ± 30 Gt (Marland and Rotty, 1984; Andres *et al*., 1999) (with updates through 2003 online at http://cdiac.ornl.gov/trends/emis/tre_glob.htm). Land use change from 1850 to 2003, mostly from the clearing of forests, added another 162 ± 160 Gt (DeFries *et al*., 1999; Houghton, 1999a)(with updates through 2000 online at http://cdiac.ornl.gov/trends/landuse/houghton/houghton.html. We extrapolated the total through 2003 based on the assumption that the fluxes in 2001-2003 were the same as that in 2000.) . The rate of fossil-fuel consumption in any recent year would have required, for its production, more than 400 times the current global primary production (total plant growth) of the land and oceans combined (Dukes, 2003). This has led to a rapid increase in the concentration of CO_2 in the atmosphere since the mid-nineteenth century, with atmospheric CO_2 rising by 31% (i.e., from 287 ppm to 375 ppm in 2003; the increase from the mid-eighteenth century was 35%).

In 2003 the three major countries of North America (Canada, Mexico, and the United States) together accounted for carbon emissions from fossil-fuel combustion of approximately 1.86 ± 0.2 Gt C, or about 27% of the global total. The United States, the world's largest emitter of carbon dioxide, was responsible for 86% of the North American total. Per capita emissions in 2003 were 5.4 ± 0.5 metric ton in the United States, 5.0 ± 0.55 metric ton in Canada, and 0.9 ± 0.1 metric ton in Mexico. Per capita emissions in the United States were nearly 5 times the world average, 2.5 times the per capita emissions for Western Europe, and more than 8 times the average for Asia and Oceania (DOE EIA, 2005). The world's largest countries, China and India, have total carbon emissions from fossil-fuel combustion and the flaring of natural gas that are substantially lower than those in the United States. The 2003 total for China was 61% of that in the United States, and the total for India was 18% that of the United States. Per capita emissions for China and India in 2003 were 14% and 5%, respectively, of the U.S. rate (DOE EIA, 2005).

ASSESSING GLOBAL AND REGIONAL CARBON BUDGETS

Changes in the carbon content of the oceans and plants and soils on land can be evaluated with at least five different approaches—flux measurements, inventories, inverse estimates based on atmospheric CO_2, process models, and calculation as a residual. The first method, direct measurement of carbon flux, is well developed over land for measurements over the spatial scale of up to 1 km^2, using the eddy flux technique (Wofsy *et al*., 1993;, Baldocchi and Valentini, 2004). Although eddy flux measurements are now collected at more than 100 networked sites, spatial scaling presents formidable challenges due to spatial heterogeneity. To date, estimates of continental-scale fluxes based on eddy flux must be regarded as preliminary. Over the oceans, eddy flux is possible (Wanninkhof and McGillis, 1999), but estimates based on air-sea CO_2 concentration difference are more widely used (Takahashi *et al*., 1997).

Inventories, based on measuring trees on land (Birdsey and Heath, 1995) or carbon in ocean-water samples (Takahashi *et al*., 2002;, Sabine *et al*., 2004a), can provide useful constraints on changes in the size of carbon pools, though their utility for quantifying short-term changes is limited. Inventories were the foundation of the recent conclusion that 118 Gt of anthropogenic carbon has entered the oceans (Sabine *et al*., 2004a) and that forests in the mid-latitudes of the Northern Hemisphere sequestered 0.6 to 0.7 Gt C yr^{-1} in the 1990s (Goodale *et al*., 2002). Changes in the atmospheric inventory of O_2 (Keeling *et al*., 1996) and ^{13}C in CO_2 (Siegenthaler and Oeschger, 1987) provide a basis for partitioning CO_2 flux into land and ocean components.

Process models and inverse estimates based on atmospheric CO_2 (or CO_2 in combination with ^{13}C or O_2) also provide useful constraints on carbon stocks and fluxes. Process models build from understanding the underlying principles of atmosphere/ocean or atmosphere/ecosystem carbon exchange to make estimates over scales of space and time that are relevant to the global carbon cycle. For the oceans, calibration against observations with tracers (Broecker *et al*., 1980) (^{14}C and chlorofluorocarbons) tends to nudge a wide range of models toward similar results. Sophisticated models with detailed treatment of the ocean circulation, chemistry, and biology all reach about the same estimate for the current ocean carbon sink, 1.5 to 1.8 Gt C yr^{-1} (Greenblatt and Sarmiento, 2004), and while uncertainties on these estimates are about ±50%, they are in quantitative agreement with data-inventory approaches. Models of the land carbon cycle take a variety of approaches. They differ substantially in the data used as constraints, in the processes simulated, and in the level of detail (Cramer *et al*., 1999; Cramer *et al*., 2001). Models that take advantage of satellite data have the potential for comprehensive coverage at high spatial resolution (Running *et al*., 2004), but only over the time domain with available satellite data. Flux components related to human activities, for example deforestation, have been modeled based on historical land use (Houghton, 1999b). At present, model estimates are uncertain enough that they are often used most effectively in concert with other kinds of estimates (e.g., Peylin *et al*., 2005).

Inverse estimates based on atmospheric gases (CO_2, ^{13}C in CO_2, or O_2) infer surface fluxes based on the spatial and temporal pattern of atmospheric concentration, coupled with information on atmospheric transport (Newsam and Enting, 1988). The atmospheric concentration of CO_2 is now measured with high precision at approximately 100 sites worldwide, with many of the stations added in the last decade (Masarie and Tans, 1995). The ^{13}C in CO_2 and high-precision O_2 are measured at far fewer sites. The basic approach is a linear Bayesian inversion (Tarantola, 1987; Enting, 2002), with many variations in the time scale of the analysis, the number of regions used, and the transport model. Inversions have more power to resolve year-to-year differences than mean fluxes (Rodenbeck *et al*., 2003; Baker *et al*., 2006). Limitations in the accuracy of atmospheric inversions come from the limited density of concentration measurements, especially in the tropics, uncertainty in the transport, and errors in the inversion process (Baker *et al*. 2006). Recent studies that use a number of sets of CO_2 monitoring stations (Rodenbeck *et al*. 2003), models (Gurney *et al*., 2003; Law *et al*., 2003; Gurney *et al*., 2004; Baker *et al*., 2006), temporal scales, and spatial regions (Pacala *et al*., 2001), highlight the sources of the uncertainties and appropriate steps for managing them.

A final approach to assessing large-scale CO_2 fluxes is solving as a residual. At the global scale, the net flux to or from the land is often calculated as the residual left after accounting for fossil emissions, atmospheric increase, and ocean uptake (Post *et al*., 1990). Increasingly, the need to treat the land as a residual is receding, as the other methods improve. Still, the existence of constraints at the level of the overall budget injects an important connection with reality.

RECENT DYNAMICS OF THE UNMANAGED CARBON CYCLE

Of the approximately 466 ± 160 Gt carbon added to the atmosphere by human actions since 1850, only about 187 ± 5 Gt remain. The “missing carbon” must be stored, at least temporarily, in the oceans and in ecosystems on land. Based on a recent ocean inventory, 118 ± 19 Gt of the missing carbon has now been identified in the oceans (Sabine *et al*., 2004a). This leaves about 161 ± 160 Gt that must be stored on land (with most of the uncertainty due to the uncertainty in emissions from land use). Identifying the processes responsible for the uptake on land, their spatial distribution, and their likely future trajectory has been one of the major goals of carbon cycle science over the last decade.

Much of the recent research on the global carbon cycle has focused on annual fluxes and their spatial and temporal variation. The temporal and spatial patterns of carbon flux provide a pathway to understanding the underlying mechanisms. Based on several different approaches, carbon uptake by the oceans averaged 1.7 ± 0.3 Gt C yr^{-1} for the period from 1992–1996 (Takahashi *et al*., 2002; Gloor *et al*., 2003; Gurney *et al*., 2003; Matear and McNeil, 2003; Matsumoto *et al*., 2004). The total anthropogenic flux is this amount, plus 0.45 Gt yr^{-1} of preindustrial outgasing, for a total of 2.2 ± 0.4 Gt yr^{-1}. This rate represents an integral over large areas that are gaining carbon and the tropics, which are losing carbon (Takahashi *et al*., 2002; Gurney *et al*., 2003; Gurney *et al*., 2004; Jacobson *et al*., 2006). Interannual variability in the ocean sink for CO_2, though substantial (Greenblatt and Sarmiento, 2004), is much smaller than interannual variability on the land (Baker *et al*., 2006).

In the 1990s, carbon releases from land-use change were more than balanced by ecosystem uptake, leading to a net sink on land (without accounting for fossil-fuel emissions) of approximately 1.1 Gt C yr^{-1}

(Schimel *et al*., 2001; Sabine *et al*., 2004b). The dominant sources of recent interannual variation in the net land flux were El Niño and the eruption of Mt. Pinatubo in 1991 (Bousquet *et al*., 2000; Rodenbeck *et al*., 2003; Baker *et al*., 2006), with most of the year-to-year variation in the tropics (Fig. 2-3). Fire likely plays a large role in this variability (van der Werf *et al*., 2004).

Figure 2-3. The 13-model mean CO_2 flux interannual variability (Gt C yr^{-1}) for several continents (solid lines) and ocean basins (dashed lines). (A) North Pacific and North America, (B) Atlantic north of 15ºN and Eurasia, (C) Australasia and Tropical Pacific, (D) Africa, and (E) South America (note the different scales for Africa and South America) (from Baker *et al*., 2006).

On a time scale of thousands of years, the ocean will be the sink for more than 90% of the carbon released to the atmosphere by human activities (Archer *et al*., 1998). The rate of CO_2 uptake by the oceans is, however, limited. CO_2 enters the oceans by dissolving in seawater. The rate of this process is determined by the concentration difference between the atmosphere and the surface waters and by an air-sea exchange coefficient related to wave action, wind, and turbulence (Le Quéré and Metzl, 2004). Because the surface waters represent a small volume with limited capacity to store CO_2, the major control on ocean uptake is at the level of moving carbon from the surface to intermediate and deep waters. Important contributions to this transport come from the large scale circulation of the oceans, especially the sinking of cold water in the Southern Ocean and, to a lesser extent, the North Atlantic.

On land, numerous processes contribute to carbon storage and carbon loss. Some of these are directly influenced through human actions (e.g., the planting of forests, conversion to no-till agriculture, or the burying of organic wastes in landfills). The human imprint on others is indirect. This category includes ecosystem responses to climate change (e.g., warming and changes in precipitation), changes in the composition of the atmosphere (e.g., increased CO_2 and increased tropospheric ozone), and delayed consequences of past actions (e.g., regrowth of forests after earlier harvesting). Early analyses of the global carbon budget (e.g., Bacastow and Keeling, 1973) typically assigned all of the net flux on land to a single mechanism, especially fertilization of plant growth by increased atmospheric CO_2. Recent evidence emphasizes the diversity of mechanisms.

The Carbon Cycle of North America

By most estimates, the land area of North America is currently a sink for carbon, in the absence of emissions from fossil-fuel combustion. This conclusion for the continental scale is based mainly on the results of atmospheric inversions. Several studies address the carbon balance of particular ecosystem types [e.g., forests (Kurz and Apps, 1999; Goodale *et al*., 2002; Chen *et al*., 2003)]. Pacala and colleagues

(Pacala *et al*., 2001) used a combination of atmospheric and land-based techniques to estimate that the 48 contiguous U.S. states are currently a carbon sink of 0.3 to 0.6 Gt C yr^{-1}. This estimate and a discussion of the processes responsible for recent sinks in North America are updated in chapter 3. Based on inversions using 13 atmospheric transport models, North America was a carbon sink of 0.97 Gt C yr^{-1} from 1991–2000 (Baker *et al*., 2006). Over the area of North America, this amounts to an annual carbon sink of 39.6 g C m^{-2} yr^{-1}, similar to the sink inferred for all northern lands (North America, Europe, Boreal Asia, and Temperate Asia) of 32.5 g C m^{-2} yr^{-1} (Baker *et al*., 2006).

Very little of the current carbon sink in North America is a consequence of deliberate action to sequester carbon. Some is a collateral benefit of steps to improve land management, for increasing soil fertility, improving wildlife habitat, etc. Much of the current sink is unintentional, a consequence of historical changes in technologies and preferences in agriculture, transportation, and urban design.

CARBON CYCLE OF THE FUTURE

The future trajectory of carbon sinks in North America is very uncertain. Several trends will play a role in determining the sign and magnitude of future changes. One important controller is the magnitude of future climate changes. If the climate warms significantly, much of the United States could experience a decrease in plant growth and an increase in the risk of wildfire (Bachelet *et al*., 2003), especially if the warming is not associated with substantial increases in precipitation. Exactly this pattern—substantial warming with little or no change in precipitation—characterizes North America in many of the newer climate simulations (Rousteenoja *et al*., 2003). If North American ecosystems are sensitive to elevated CO_2, nitrogen deposition, or warming, plant growth could increase (Schimel *et al*., 2000). The empirical literature on CO_2 and nitrogen deposition is mixed, with some reports of substantial growth enhancement (Norby *et al*., 2005) and others reporting small or modest effects (Oren *et al*., 2001; Shaw *et al*., 2002; Heath *et al*., 2005).

Overall, the carbon budget of North America is dominated by carbon releases from the combustion of fossil fuels. Recent sinks, largely from carbon uptake in plants and soils, may approach 50% of the recent fossil fuel source (Baker *et al*., 2006). Most of this uptake appears to be a rebound, as natural and managed ecosystems recover from past disturbances. Little evidence supports the idea that these ecosystem sinks will increase in the future. Substantial climate change could convert current sinks into sources (Gruber *et al*., 2004).

In the future, trends in the North American energy economy may intersect with trends in the natural carbon cycle. A large-scale investment in afforestation could offset substantial future emissions (Graham, 2003). Costs of this kind of effort would, however, include the loss of the new forested area from its previous uses, including grazing or agriculture, plus the energy costs of managing the new forests, plus any increases in emissions of non-CO_2 greenhouse gases from the new forests. Large-scale investments in biomass energy would have similar costs but would result in offsetting emissions from fossil-fuel combustion, rather than sequestration (Giampietro *et al*., 1997). The relative costs and benefits of investments in afforestation and biomass energy will require careful analysis (Kirschbaum, 2003). Investments in other energy technologies, including wind and solar, will require some land area, but the impacts on the natural carbon cycle are unlikely to be significant or widespread (Hoffert *et al*., 2002; Pacala and Socolow, 2004).

Like the present, the carbon cycle of North America during the next several decades will be dominated by fossil emissions. Geological sequestration may become an increasingly important component of the budget sheet. Still, progress in controlling the net release to the atmosphere must be centered on the production and consumption of energy rather than the processes of the unmanaged carbon cycle. North America has many opportunities to decrease emissions (Chapter 4). Nothing about the status of the unmanaged carbon cycle provides a justification for assuming that it can compensate for emissions from fossil fuel combustion.

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Table 1. Sinks of carbon for 1980–90 in the coterminous United States (in Gt C yr^{-1}).

Category	Low	High	Land area 1980–90 (10^6 ha)	Houghton *et al.* (8)	Birdsey and Heath (12)
Forest trees	0.11	0.15	247–247	0.06 [a]	0.11
Other forest organic matter	0.03	0.15	247–247	– 0.01	0.18
Cropland soils	0.00	0.04	185–183	0.14	—
Nonforest, non-cropland (woody encroachment)	0.12 [b]	0.13 [b]	334–336 [c]	0.12	—
Wood products	0.03	0.07	—	0.03	0.03
Reservoirs, alluvium, colluvium	0.01	0.04	—	—	—
Exports minus imports of food, wood	0.04	0.09	—	—	—
Fixed in the United States but exported by rivers	0.03	0.04	—	—	—
"Apparent"[d] U.S. sink without woody encroachment	0.25	0.58	766	0.15–0.23 [e]	0.31
"Apparent"[d] U.S. sink including woody encroachment	0.37	0.71	766	0.15–0.35 [e]	—
Sink [f]	0.03	0.58	766	0.15–0.35 [e]	0.31

[a] Assumes that the 0.05 Gt C yr^{-1} estimated in (8) to be accumulating in western pine woodlands as a result of the suppression is assigned to forest instead of row 4.
[b] These numbers are not bounds, but rather the only two existing estimates.
[c] Total area for all lands other than forest and croplands. Possible woody encroachment because of fire suppression on up to about two-thirds of this land (10,16).
[d] By "apparent" sink, we mean the net flux from the atmosphere to the land that would be estimated in an inversion. It includes all terms in the table.
[e] Lower bound reflects uncertainty in the estimates for the effects of fire suppression.
[f] Excludes sinks caused by the export/import imbalance for food and wood products and river exports because these create corresponding sources outside the United States.
Source: Pacala *et al*. (2001)

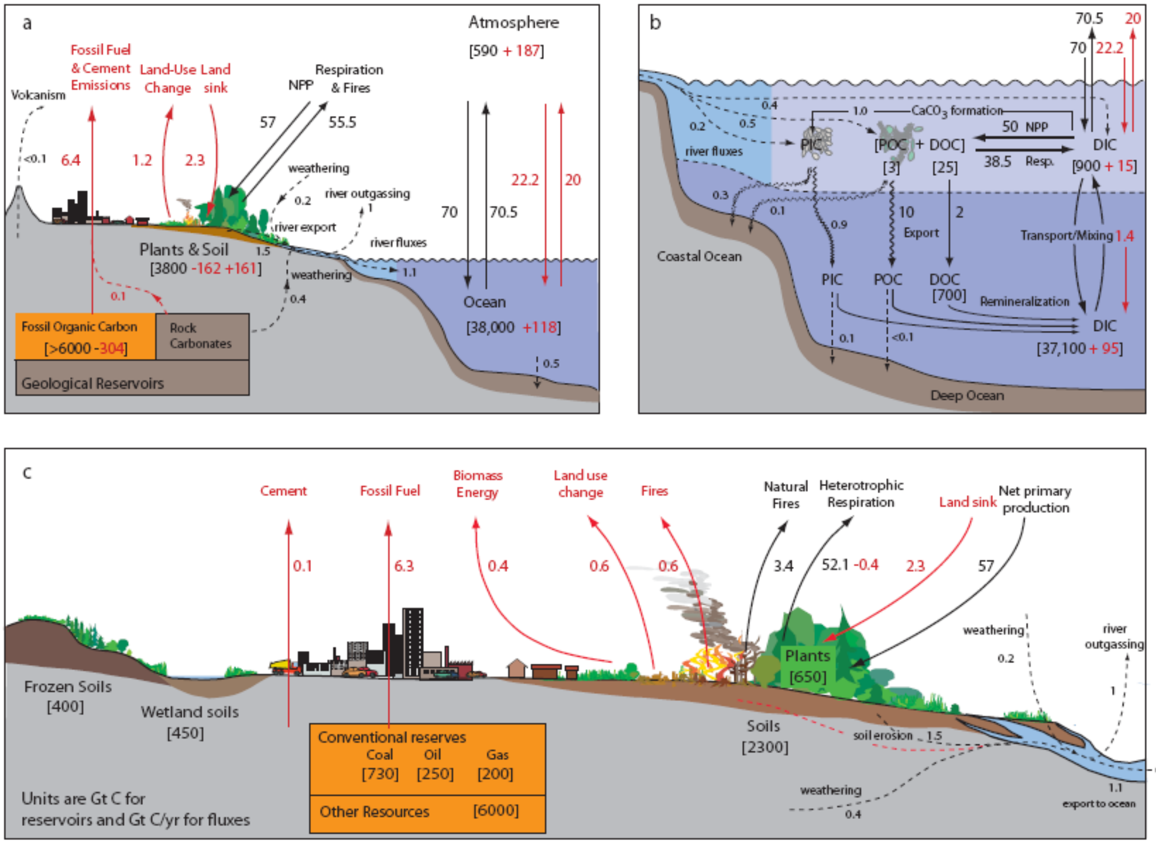

Figure 2-1. Schematic representation of the components of the global carbon cycle. The three panels show (A) the overall cycle, (B) the details of the ocean cycle, and (C) and the details of the land cycle. For all panels, carbon stocks are in brackets, and fluxes have no brackets. Pre-anthropogenic stocks and fluxes are in black. Anthropogenic perturbations are in red. For stocks, the anthropogenic perturbations are the cumulative total since 1850. Anthropogenic fluxes are means for the 1990s. Redrawn from Sabine *et al*. (2004b) with updates as discussed in the text.

1

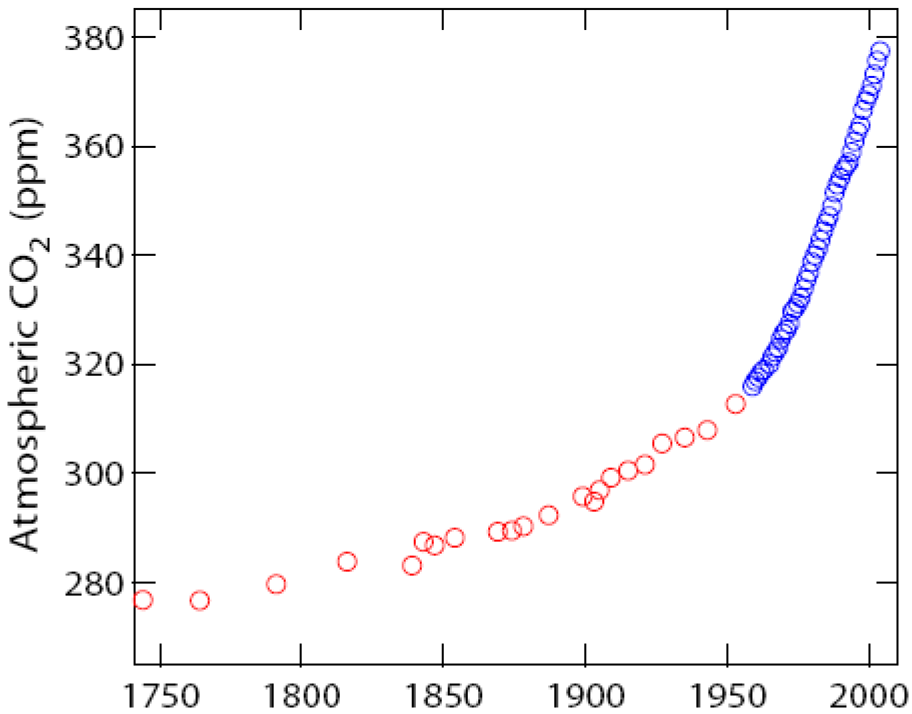

Fig. 2-2. Atmospheric CO_2 concentration from 1850 to 2005. The data prior to 1957 (red circles) are from the Siple ice core (Friedli *et al*., 1986). The data since 1957 (blue circles) are from continuous atmospheric sampling at the Mauna Loa Observatory (Hawaii) (Keeling *et al*., 1976; Thoning *et al*., 1989) (with updates available at http://cdiac.ornl.gov/trends/co2/sio-mlo.htm).

2

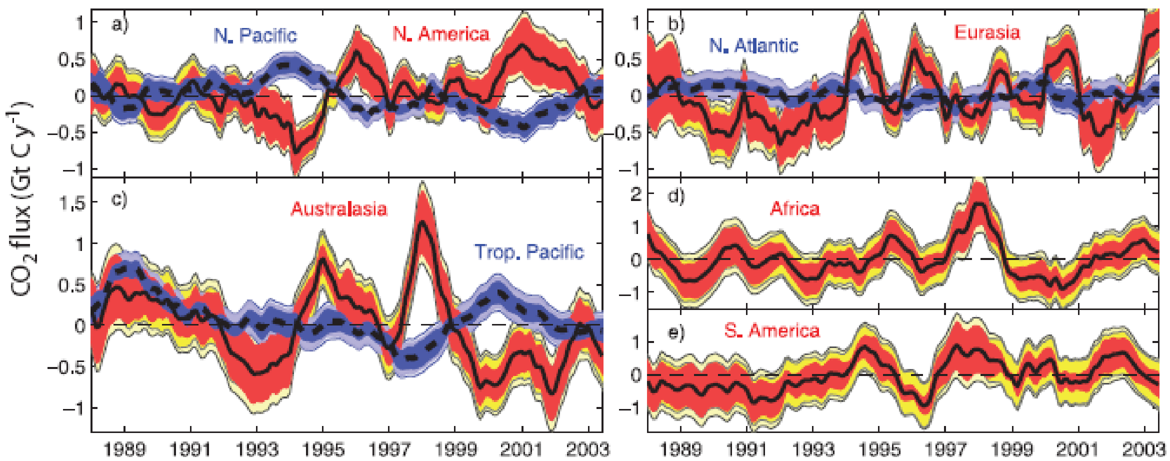

Figure 2-3. The 13-model mean CO_2 flux interannual variability (Gt C yr^{-1}) for several continents (solid lines) and ocean basins (dashed lines). (A) North Pacific and North America, (B) Atlantic north of 15ºN and Eurasia, (C) Australasia and Tropical Pacific, (D) Africa, and (E) South America (note the different scales for Africa and South America) [from (Baker *et al*., 2006)].

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