Global Carbon Cycle

I. Intro - why study the carbon cycle?
  A. carbon is the key element of life
    1. most fundamental biogeochemical cycle
  B. changes in atmos. CO_2 as a result of fossil fuel burning
    1. potential global warming
    2. crucial to understand how the carbon cycle operates
      a. also linkages between CO_2 and climate
  C. carbon cycle is complex - **C cycle box model**
    1. operate on a variety of time scales
      a. short-term and long-term components
      b. cycling of organic and inorganic C
  D. geological processes operating on million year time scales
  E. biological processes operating on annual time scales
    1. interactions between the 2 are important

II. Major reservoirs **Fig. 8-3**
  A. vast majority of C tied up in sedimentary reservoirs that cycle very slowly
    1. think of atmosphere, oceans and land as the major active reservoirs
      a. active on short time scales
    2. the atmosphere is a rel. small reservoir but it turns over rapidly
  B. large gross exchange fluxes to and from atmosphere **show my model**
    1. compare terr pp (60) vs. loss to oceans (0.4)
      a. also marine pp (50) vs. burial in sediments (0.1)
    2. most primary production (uptake of CO_2) is respired (CO_2 goes back to atmos.)
    3. small net fluxes
    4. atmospheric reservoir has a short residence time - ~3 yrs
  C. problem with adding fossil fuel CO_2 to atmosphere
    1. taking carbon from a long term/geologic reservoir and transferring it a short term reservoir
    2. this system may be balanced on long time scales
      a. relatively balanced (within certain limits) on shorter time scales
    3. such a transfer from reservoirs that operate on different time scales may exceed the capacity of the short term feedback mechanisms to control the system

III. Atmosphere
  A. mostly C in atmosphere exists as CO_2
    1. some methane and CO
    2. other trace carbon gasses - more impt. for other elemental cycles (ie, DMS in S cycle)
  B. atmospheric CO_2 show a rapid recent increase in recent time **Fig. 1-2 and 1-3**
  C. rapid increase begins with the Industrial Revolution and rise of population in Europe and America
  D. see seasonal variations in recent increase **Barrow and S Pole data**
    1. uptake in spring when there is net plant growth, release in fall from net respiration
    2. seasonality offset 6 months between northern to southern hemisphere
      a. southern hemisphere amplitude is also smaller

b. northern hemisphere has more extensive seasonal forests
c. close tracking between N and S hemisphere
(i) rel. rapid mixing of atmosphere

E. prior to large scale human activity the system also showed natural variability
1. large glacial-interglacial changes - 50-80 ppm **Vostok ice core data**
2. Holocene changes much smaller back to **Fig. 1-3**
a. recent high resolution ice core record suggest changes of ±10 ppm over last 1000 yr
b. natural variability in the Holocene is a second order change as compared to glacial-interglacial changes or anthropogenic increase
3. allows us to think about a near constant pre-industrial interglacial CO_2 level of ~280 ppm

F. recent increase mainly due to fossil fuel burning **Fig. 6-2**
1. some due to land use changes/deforestation
a. deforestation
(i) lack of photosynthesis taking up CO_2
(ii) burning of wood produces CO_2
2. inputs from the terrestrial biosphere (e.g., deforestation) likely accounted for most of the observed changes in the 19th century
a. initial increases in CO_2 pre-date industrial revolution
b. these processes appear to have leveled off in the past 50 yr
3. most recent increases are likely due to fossil fuel

G. recent results suggest that deforestation in the tropics may be partially balanced by N. Hemisphere forest expansion/regrowth
1. see new IPCC budget (note d in table) **Table 2**

IV. Oceans

A. the oceans are the largest active reservoir in the carbon cycle
1. primarily DIC - dissolved inorganic carbon

B. oceans link the active/short term cycles and the long-term/geological cycles
1. represent an important sink for fossil fuel CO_2

C. oceanic processes in the global carbon cycle **show ocean figure**
1. focuses on the biological cycle and its effect in mitigating the effects of adding fossil fuel
2. ocean/atmos. system also involved in a more long-term cycle involving weathering rxns.
3. these rxns. are prob. important in terms of long-term controls on atmos. CO_2 and O_2
a. atmos. CO_2 -> riverine bicarbonate -> neutralized in oceans -> atmos. CO_2
b. more later

D. processes that remove atmospheric CO_2 from sfc. waters
1. gas exchange
2. biological pump
3. bottom water formation

E. gas exchange
1. primary transport mechanism between ocean and atmos.
a. $CO_2\,(g) \rightleftharpoons CO_2\,(aq)$
2. in the absence of other processes this only leads to equilibration of the sfc. ocean with the atmos
3. if CO_2 behaved like a simple gas the oceans would only take up ~3% of the fossil fuel input
4. the ability of the oceans to take up large amounts of CO_2 depend on its acid-base chemistry

5. rxn. between diss. carbonate ion and CO_2
    a. $CO_3^{-2} + H_2O + CO_2 \rightarrow 2\ HCO_3^-$
    b. buffering rxn that drives CO_2 to HCO_3^-
    c. this titrate CO_2 added by gas exchange
6. sfc. waters reach equilibrium with atmos. CO_2 in about a year
    a. fast enough to keep pace with mans activity
    b. but surface ocean doesn't have a large enough capacity to neutralize all of this addition
        (i) sfc. ocean too "small"
    c. need a way to move CO_2 to deep waters and sediments

F. biological pump
1. primary production and calcite ppt. consume inorganic carbon species
2. these are then removed via particle fluxes
3. thru the interactions of the carbonate system this lowers the partial pressure of CO_2 in the ocean (pCO_2) which enhances gas exchange ($\Delta pCO_2 < 0$)
4. the biological pump transports CO_2 to the deep ocean in the form of OM or calcite shells
5. limitations of the biologic pump
    a. biological pump controlled by availability of nutrients (N, P, Fe ?)
    b. more CO_2 doesn't imply more biological uptake if these other nutrients are limiting

G. bottom water formation
1. removes CO_2 by physical movement of water away from surface
2. solubility pump
3. CO_2 is more soluble in colder waters

H. intermediate and deep water processes that affect CO_2
1. OM oxidation - produces CO_2
2. calcite dissolution
    a. excess CO_2 from OM oxidation can react with calcite in marine sediments and in sinking particles

I. when coupled to the biological pump this transports some atmos. CO_2 to deep ocean
1. "stores" it as HCO_3^-

J. upwelling
1. intermediate waters are enriched in DIC
    a. mixing with deep waters
    b. OM oxidation and calcite dissolution
    c. most CO_2 produced by these processes reacts with carbonate
    d. still get some CO_2 increase
2. upwelling of these waters leads to sfc water in upwelling regions having excess pCO_2 ($\Delta pCO_2 > 0$)
    a. this conc gradient means that the oceans here should be a source of CO_2 to the atmosphere
    b. leads to an outgassing of the CO_2 in these waters **Fig. 8-13 and Tak figure**
    c. upwelling regions where intermediate water upwells
    d. non-upwelling regions of high productivity are net sinks
        (i) also polar regions where bottom waters form

K. integration of the data in Fig.8-13 leads to ocean uptake of CO_2 in IPCC calcs. in Table 2
1. this calc. attempts to assess the rel. short term sinks for excess atmos. CO_2 due to anthopogenic activitites
2. prior to anthropogenic activity the oceans behaved a little differently

V. Time scales of the oceanic carbon cycle **2nd ocean C cycle figure**

- A. oceanic processes are relatively slow in comparison to the rate at which man is burning fossil fuels
- B. bottom water circulation occurs on time scales of hundreds of years
- C. these waters will equilibrate with atmospheric CO_2 on these long time scales
- D. deep sea sediments will equilibrate with atmosphere on time scales of thousands of years.
  1. this is where the bulk of the neutralizing capacity for atmos. CO_2 resides
- E. the time scales of oceanic processes are too slow to deal with the relatively rapid increases in CO_2 due to mans activities
- F. implies that the oceans do not respond rapidly enough to take up all excess CO_2
  1. in part this is why atmos concs. are increasing
- G. this does not mean that the oceans don't affect atmospheric CO_2 or haven't modulated increases in atmospheric concentrations
  1. calculations suggest that the net carbon uptake by the oceans is a significant fraction of the total fossil fuel carbon put into the atmosphere **back to IPCC Table 2**

VI. Terrestrial Systems

- A. consists of a variety of materials that turnover on different time scales **Fig. 5-17**
  1. soil humus
     - a. altered remains of vascular plants
     - b. humic substances and humus
       - (i) contain a large number of aromatic rings with phenolic (-OH) and –COOH groups
       - (ii) the residue of the microbial degradation of lignin (lignocellulose)
  2. land plant tissue
     - a. living biomass and undecomposed litter
  3. methane
     - a. terr systems are also a significant source of atmospheric methane
     - b. more later
- B. terr. PP rates are significant compared to marine values **show my model**
  1. process similar amounts of carbon
- C. terr. systems also “store” excess CO_2 differently than the oceans **2nd Fig. 8-3**
  1. soil humus vs. diss. bicarbonate
- D. this may be of some importance in understanding how these different systems respond to incr. CO_2 and potential global warming **2nd Fig. 5-17**
  1. increasing CO_2 and possible associated global warming might increase terr. primary prod.
     - a. temp. effect and CO_2 fertilization effect
     - b. negative feedback on CO_2/global warming
  2. could also increase rates of microbial decomposition of terr. OM (soil humus)
     - a. positive feedback for global warming