THE OCEAN CARBON PUMPS

How do the oceanic carbon pump control atmospheric pCO$_2$? Theory and Models.

Bibliography and discussion by Irina Marinov, Oct 2011

The bibliography below shows some of the most recent developments in our theoretical understanding of the ocean carbon pumps. We discuss, in order, the organic carbon pump, the carbonate pump and the solubility pump. We end with a discussion of how the carbon pumps will respond to future climate change, and the resulting feedbacks in the system.

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Notation:
BM = Box Model
GCM = (three dimensional) General Circulation Model

1. Defining the carbon pumps
Given that inorganic carbon exists interchangeably as carbon dioxide, carbonate ion, or bicarbonate ion, the inorganic carbon content of the ocean is best characterized by DIC or dissolved inorganic carbon, the sum of these three. The carbon chemistry in water is such that CO$_2$ reacts with the other species (hydrolysis); hence most of DIC exists in the carbonate and bicarbonate form. The ocean holds about 60 times more CO$_2$ than the atmosphere, suggesting that the ocean exerts a dominant control on atmospheric CO$_2$. The reason for this is a combination of hydrolysis and a set of physical, chemical and biological processes collectively known as the ocean carbon pumps. These pumps contribute to a higher concentration of DIC in the deep ocean relative to the surface, which reduces atmospheric CO$_2$ relative to what it would be otherwise.


Volk and Hoffert (1985) first defined the efficiency of the oceanic carbon pump as the surface to deep difference in DIC. The larger the surface to deep gradient in DIC, the less CO$_2$ stays in the atmosphere. Cold waters hold more CO$_2$ than warm waters. Hence, the cold abyssal ocean filled with cold waters formed in high latitudes holds more DIC than warm surface waters. This solubility pump accounts for one third of the surface to deep DIC difference. The formation (at the surface) and dissolution (deeper in the watercolumn) of CaCO$_3$ shells by some plankton results in a transfer of DIC to the deep, a process called the carbonate pump. The soft tissue pump (also called the organic carbon pump) encompasses the formation of organic matter at the ocean surface via photosynthesis, its export into the deep ocean and its gradual dissolution back into the dissolved...
inorganic carbon and nutrients. The soft tissue and the carbonate pump both transfer DIC to the deep ocean and are collectively known as the biological pump.

2. The organic (soft-tissue) carbon pump:


The three box model studies above first pointed out that an increase in nutrient utilization in the high latitudes (performed in these models by depleting nutrients in the high latitude box) results in increased biological productivity and increased storage of carbon in the ocean, hence less CO₂ in the atmosphere. This early research led to two important ideas: high latitude regions are more important in determining atmospheric pCO₂ than low latitudes, despite their much smaller area, and nutrient utilization and atmospheric pCO₂ are tightly linked. Stronger nutrient utilization, especially in high latitudes, increases the efficiency of the carbon pump and lowers atmospheric pCO₂.


This study attempts to separate the total ocean carbon pump into "potential" carbonate, "potential" soft tissue and "potential" solubility pumps (assuming gas exchange is infinitely fast such that surface CO₂ is in equilibrium with the atmosphere), and corresponding disequilibrium components. The focus is on the mean vertical gradient of DIC. See also discussion in Ch 8 of the textbook below.

- Sarmiento J.L. and Gruber, N. (2004): Ocean Biogeochemical Dynamics, Princeton University Press. Recent textbook with good discussion of carbon dynamics, see chapters 8 (carbon cycle basics), 9 (calcium carbonate pump) and 10 (carbon and future climate) in particular.


This paper shows that atmospheric CO₂ and global biological export production are controlled by separate regions of the Southern Ocean. Atmospheric pCO₂ is controlled mainly by the biological pump and circulation in the Antarctic deep-water formation region (close to the Antarctic continent), whereas global export production is controlled mainly by the biological pump and circulation in the Subantarctic region where intermediate and mode waters form. The existence of a biogeochemical divide separating the Antarctic from the Subantarctic suggests that it may be possible for climate change or human intervention to modify one of these (atmospheric pCO₂ or global biological production) without greatly altering the other.

The organic carbon pumps in box models and GCMs are compared. Deep water in the three-box model is relatively well equilibrated with respect to the $pCO_2$ of the atmosphere while deep water in the GCM tends to be poorly equilibrated. This makes the organic pump inherently stronger in the GCM than in the three-box model. Secondly, this paper shows that there are more ways to change the organic pump in the GCM than in the box model. In particular, changes in deep-water formation that alter the mix of northern and southern deep water can make the organic pump in the GCM weaker or stronger without changes in polar nutrient utilization. In the three box models this is not possible since only one high latitude box is represented; polar nutrient depletion is the only avenue for producing a stronger organic pump in the three-box model.


The air-sea CO$_2$ balance is best understood by analyzing the fraction of total nutrients in the ocean that is remineralized, and thus associated with carbon, versus the fraction that is "preformed" i.e. injected into the deep ocean without being associated with carbon. Preformed nutrients are those nutrients that sink or are subducted into the ocean interior without having fueled primary productivity at the surface; they are the signature of an inefficient biological pump. Remineralized nutrients are those respired throughout the water column; these are stoichiometrically associated with remineralized carbon. These theoretical developments (verified by a set of GCM simulations in each paper) show that in the absence of carbonate and solubility pumps and assuming perfect air-sea CO$_2$ equilibrium, atmospheric CO$_2$ can be expressed as a sum of exponential functions of the globally averaged preformed nutrient concentration (or of the globally averaged remineralized nutrient). If for some reason global preformed nutrients were to decrease (due, for example, to enhanced surface production) there would be an increase in the net remineralized nutrient and carbon in the ocean, and hence a global increase in the efficiency of the biological pump and a drop in atmospheric $pCO_2$.


Changes in winds and mixing can shift the balance of deepwater formation between the North Atlantic (where preformed nutrients are low) and the Southern Ocean (where preformed nutrients are high). Such a shift changes the net oceanic preformed nutrient and hence atmospheric $pCO_2$, even if surface nutrients do not change. Contrary to conventional wisdom, a decrease in atmospheric CO$_2$ can occur even when surface nutrients are constant and export production drops. Shifted westerlies that flush respired CO$_2$ out of the deep ocean via enhanced Circumpolar Deep water upwelling.

3. The carbonate pump:

Good Literature Reviews:

Here the authors review the biological-physical hypotheses for glacial-interglacial change and propose a synthesis scenario that combines several of the proposed scenarios above into a single
framework. The paper also includes a good description of the carbonate pump, including the expected changes in the carbonate pump from glacial to interglacial periods.

- **Sarmiento J.L. and Gruber, N. (2004): Ocean Biogeochemical Dynamics, Princeton University Press.** The carbonate pump is a long and complex topic, reviewed well in Chapter 8 of this textbook, with a long list of references.


**Some recent papers:**


- **Goodwin, P., R. G. Williams, M. J. Follows, and S. Dutkiewicz, Ocean-atmosphere partitioning of anthropogenic carbon dioxide on Centennial Timescales, Glob. Biogeochem. Cycles 21(1), GB1014, doi:10.1029/2006GB002810, (2007).** Develops a simple theory (along the lines of Ito et al. 2005 and Marinov et al. 2008) to predict how atmospheric $p\text{CO}_2$ will evolve, for given $\text{CO}_2$ emissions and assuming equilibrium of ocean $\text{CO}_2$ with the atmosphere. The MIT GCM predicts that future carbon emissions must be restricted to a total of 700 GtC to achieve $p\text{CO}_2$ stabilization at present-day transient levels.


The framework from Goodwin et al. 2007 is extended to incorporate the long-term effect of changes in the marine CaCO$_3$ cycle (and ALK) on atmospheric $p\text{CO}_2$.


This paper complements the analytical work of Ito and Follows (2005) and Marinov et al. (2008) on the soft tissue pump, by considering also the carbonate pump. A simple analytical framework is developed relating the atmospheric partial pressure of CO$_2$ to both the globally-averaged concentrations of respired carbon and dissolved carbonate in the ocean. The theory and a 3D ocean model are used to show that the response of atmospheric $p\text{CO}_2$ to changes in ocean circulation is rather modest because ~30% of the change in atmospheric $p\text{CO}_2$ caused by the accumulation of respired carbon is countered by a concomitant accumulation of dissolved carbonate in deep waters. Paper suggests that a synchronously reduced rate for the deep water formation in both hemispheres could lead to the large glacial reduction in atmospheric $p\text{CO}_2$ of 80-100 ppm.

**4. The solubility pump:**

The impact of temperature on the oceanic solubility pump generates a positive feedback in the system. For example, global warming resulting from the increasing amount of carbon in the atmosphere leads to decreased solubility of CO$_2$ in surface waters, a decreased oceanic carbon uptake via the oceanic solubility pump, which in turn increases the global warming. The following papers discuss various aspects of the solubility pump.
Despite decades of research the mechanisms that regulate $pCO_2$ on glacial-interglacial timescales remain uncertain. A reason for this uncertainty is that various models disagree on the degree to which changes in chemistry of low-latitude and high-latitude surface ocean can alter atmospheric $pCO_2$. Many of the papers below discuss this high latitude versus low latitude sensitivity.


The above “Polar Skeptics” suggest that atmospheric $pCO_2$ has a greater sensitivity to low latitude surface ocean properties (and lower high latitude sensitivity) than had previously been accepted or that the 3BM studies (Sarmiento and Toggweiler 1984) suggested. These papers argue that box models are deficient in the way they represent the thermal partitioning of CO$_2$, partitioning less CO$_2$ into cold deep waters compared to General Circulation Models (GCMs). They suggest this is the case because these too simplistic models are missing key circulation and mixing features present in the real ocean; such that the exchange of CO$_2$ between warm surface waters is more vigorous in the real ocean (and in 3 dimensional ocean circulation models than in the simplified BMs). They suggest that as a result box models are overly sensitive to high latitude processes (relative to the GCMs and the real world).


Motivated by the “Polar Skeptics” and by Archer et al. 2000, this paper shows that unresolved mixing and circulation effects in box models are not the main reason for box model-GCM differences in the solubility pump. The main factor is the very different kinds of restrictions on gas exchange in polar areas. New deep water in the three-box model is too well equilibrated with atmospheric CO$_2$ while new southern deep water in GCMs is too poorly equilibrated compared to the real world. The reason is that polar outcrops in GCMs are much smaller than in box models, and they are assumed to be ice covered in an unrealistic way. The solubility pump in the three-box model can be made more realistic with a simple reduction in the area of its polar box.

- Follows, M. J., T. Ito and J. Marotzke, The wind-driven, subtropical gyres and the solubility pump of CO2. Global Biogeochem. Cycles, 16, 1113, doi:10.1029/2001GB001786 (2002). Follows et al. (2002), using an idealized general circulation and abiotic carbon cycle model, showed that the wind-driven circulation enhances the sensitivity of atmospheric $pCO_2$ to low latitude surface properties by creating a pool of relatively warm waters in the ventilated thermocline which inherit their properties from the mid-latitude surface. The model, which conserves the total amount of carbon in ocean and atmosphere, also illustrated a strong sensitivity of atmospheric $pCO_2$ to the presence or absence of wind forcing.

- Ito, T., and M. J. Follows, Upper ocean control on the solubility pump of CO2, Journal of Marine Research 61, 465-489 (2003). This paper develops a theory describing how atmospheric CO$_2$ varies with diapycnal diffusivity and
wind, based on established thermocline theory. Two limit cases for thermocline circulation are considered: the diffusive thermocline and the ventilated thermocline.


- DeVries, T., and F. Primeau, Atmospheric pCO₂ sensitivity to the solubility pump: Role of the low-latitude ocean, Global Biogeochem. Cycles, 23, GB4020, doi:10.1029/2009GB003537 (2009) DeVries and Primeau show that the impact of the disequilibrium component scales with the strength of the overturning circulation and they show (using a Green-function analysis) that the impact of the solubility component on atmospheric pCO₂ approximately scales with the average temperature of the ocean.

- Omta, A. W., S. Dutkiewicz, and M. J. Follows, Dependence of the ocean-atmosphere partitioning of carbon on temperature and alkalinity, Global Biogeochem. Cycles, 25, GB1003, doi:10.1029/2010GB003839 (2011) A recent attempt to develop further the mathematical theory for the solubility pump, assuming that CO₂ in the ocean is in equilibrium with CO₂ in the atmosphere. Theory + models suggest that atmospheric pCO₂ depends approximately exponentially on the average ocean temperature. The current ocean-atmosphere system appears to have an exponential dependence of pCO₂ on global mean ocean alkalinity, but at slightly higher alkalinitities, the dependence becomes a power law

5. The natural carbon pumps in a future warmer world:

5.1. The large role of the Southern Ocean

If the strength of the natural carbon pumps stayed constant in time, the addition of anthropogenic CO₂ would result in larger oceanic uptake. However, the strength of the natural pumps also changes. It is clear that as the ocean becomes warmer the solubility of CO₂ in water will decrease, decreasing the amount of carbon stored in the ocean associated with the solubility pump. It is less clear (and far more controversial) what will happen with the biological pump in a warmer climate. Will the biological pump increase or decrease if the stratification of the ocean increases but Southern ocean Westerlies strengthen (as expected from models and observations so far)? The answer is still up for grabs. This is one of the hot topics under debate right now (see for example the Le Quere 2007 paper in Section 4.2 below). Below are some of the landmark, highly cited studies on this very interesting topic.


What will happen with the biological pump in a warmer climate? The two studies above suggest that the efficiency of the global biological pump will decrease because enhanced westerlies over the Drake passage (associated with the observed trend towards a more positive Southern Annular Mode over the past 50 years) will result in more Southern Ocean upwelling of deep water rich in respired inorganic carbon. This will result in less carbon storage in the ocean and more outgassing to the atmosphere, i.e. a worrisome positive feedback on global warming. If increasing temperatures are responsible in the first place for the poleward shift of westerlies and enhancement of westerlies over the Drake passage, the above mechanism suggests a positive feedback between climate (or atmospheric CO₂ levels) and the ocean biological pump (this is the mechanism proposed by Toggweiler et al. 2006).


Confirms the basic results in Le Quere et al. 2007. This paper suggests that the global ocean responded to recent changes in climate by outgassing some preindustrial carbon (i.e., decreasing the natural carbon pump), partially compensating the oceanic uptake of anthropogenic CO₂. Climate change reduced the CO₂ uptake by 12% compared to a simulation where constant climate is imposed, and offset 63% of the trend in response to increasing atmospheric CO₂ alone. The response is caused by changes in wind patterns and ocean warming, with important nonlinear effects that amplify the response of oceanic CO₂ to changes in climate by > 30%.

5.2. Feedbacks in the system:

The studies below analyze the feedbacks between the ocean (and sometimes the land) carbon cycle and climate.


  Shows that the solubility and biological pumps might change in opposite directions with climate change. Increased stratification and warming result in decreased solubility pump and decreased carbon uptake, partly compensated by a more efficient biological pump (due to increased stratification). Main downside of this study is a too simplistic representation of the biological pump.


  Detailed modeling study of three feedbacks associated with the oceanic uptake of CO₂ under a warming climate: (i) warmer sea-surface temperature increased CO₂ in the surface ocean and reduced the accumulated ocean uptake by 48 Gt C. (ii) reduced meridional overturning and increased density stratification in high latitudes slowed anthropogenic CO₂ transport into the ocean interior and reduced the cumulative ocean CO₂ uptake by 41 Gt C, (iii) altered “natural” cycling of carbon in the ocean increased the cumulative ocean CO₂ uptake by 33 Gt C.

Modeling study that claims that future projected changes in the marine carbon cycle will have a modest impact on atmospheric CO₂. Sea surface warming decreases the oceanic carbon uptake (decreasing the solubility pump), increasing atmospheric CO₂ by 4% at year 2100 and 20% at year 2500. The changes of the marine biological cycle compensate the reduction in downward mixing of anthropogenic carbon (due to reduced ventilation and North Atlantic thermohaline circulation).

This controversial paper is based on the Hadley Centre fully coupled 3D ocean-atmosphere model. Under a business as usual scenario, the terrestrial biosphere acts as an overall carbon sink until 2050, but turns into a source thereafter. This is due to the dieback of the Amazon forest in a warmer and drier climate. The presence of the carbon-cycle feedbacks results in a global-mean warming of 5.5 K, as compared to 4 K without the carbon-cycle feedback.

The uptake of atmospheric CO₂ by the ocean is reduced between 7 to 10% by year 2100 compared to simulations without global warming. At high latitudes, biologically mediated changes enhance ocean CO₂ uptake, whereas in low-latitude regions the situation is reversed. Different implementations of the marine biosphere yield a range of 5 to 16% for the total reduction in oceanic CO₂ uptake until year 2100.

Landmark modeling study showing a strong positive feedback between the climate system and the land and ocean carbon cycles. Climate change reduces land and ocean uptake of CO₂, respectively by 54% and 35% at 4 x CO₂.

A coupled climate carbon cycle model study from the Hadley Centre group showed a much larger positive feedback than the French IPSL model study if future climate impacts on the carbon cycle are included. A detailed feedback analysis shows that such differences are due to two key processes: (1) Southern Ocean circulation, which primarily controls the geochemical uptake of CO₂ and (2) vegetation and soil carbon response to global warming, with the latter dominating the difference between the Hadley and IPSL models.

Results form the NCAR Climate System Model 1 coupled carbon–climate model shows that carbon sink strengths vary with the rate of fossil fuel emissions, so that carbon storage capacities of the land and oceans decrease and climate warming accelerates with faster CO₂ emissions. Furthermore, there is a positive feedback between the carbon and climate systems, so that climate warming acts to increase the airborne fraction of anthropogenic CO₂ and amplify the climate change itself.

Presents results of eleven coupled climate-carbon models forced with SRES A2 emission of CO₂ over
the 21st century. Future climate change will reduce the efficiency of the earth system to absorb the anthropogenic carbon perturbation. All models produce an increase in the fraction of total emissions that remain in the atmosphere, and most also indicate a decline in the fraction of emissions absorbed by the ocean (9 out of 11 models) and the land (10 out of 11 models). CO2 increase alone enhances both land and ocean carbon storage, whereas climate change alone releases land and ocean carbon to the atmosphere (i.e., decreases the natural ocean carbon pumps). Anthropogenic CO2 in the atmosphere is larger by 50-100 ppm if climate change is accounted for, resulting in additional climate warming of 0.1°-1.5°C.


Eight earth system models of intermediate complexity are used to project climate change until year 3000 A.D., assuming that emissions are kept at their year 2100 values after year 2100. Sea level continues to rise due to thermal expansion for several centuries after CO2 stabilization while surface temperature changes slow down after a century. The meridional overturning circulation is weakened in all models, but recovers to nearly initial values in all but one of the models after centuries. Emissions during the twenty-first century continue to impact atmospheric CO2 and climate even at year 3000. All models find that most of the anthropogenic carbon emissions are eventually taken up by the ocean (49%-62%) in year 3000, and that a substantial fraction (15%-28%) is still airborne even 900 years after carbon emissions have ceased!


The carbon cycle gives rise to two climate feedbacks: the concentration-carbon feedback, resulting from the uptake of carbon by land and ocean as a biogeochemical response to the rising atmospheric CO2 concentration, and the climate-carbon feedback resulting from the effect of climate change on carbon fluxes. In the earth system models of the Coupled Climate-Carbon Cycle Model Intercomparison Project (C4MIP), the climate-carbon feedback is positive. The concentration-carbon feedback is negative, 4 times larger than the climate-carbon feedback and more uncertain.

6. OVERVIEW / TEXTBOOKS


Textbook contains an excellent introduction to the carbon cycle. Ideal for teaching graduate level classes.


Good IPCC 2007 overview chapter - with numerous references up to 2007 - for the interaction
between land and ocean biogeochemistry with future climate change. Ocean & terrrestrial feedbacks discussion.

Contains a few good introductory chapters on the ocean carbon cycle. Textbook designed for teaching 2nd year undergraduates at Univ. of Chicago.

· **David Archer**, *The Global Carbon Cycle (Princeton Primers in Climate)*, Princeton University Press *(2010).*
Small format book, everything you need to know about carbon in the present climate and on longer glacial-interglacial timescales and beyond. Detailed, with tons of info on carbonate chemistry.

Brand new textbook, nicely combines the ocean physics (the main focus of the book) with some chemistry and biology fundamentals, with a couple of chapters on nutrients and carbon cycling.

· **The “Global Carbon Project”, http://www.globalcarbonproject.org/carbontrends**
An international project that updates all the data on atmospheric, ocean and terrestrial carbon cycles every year on their fantastic website, which includes plenty of powerpoints with their most recent updates, ideal for teaching.