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.

Contents:

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 hydrolisis 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, T. and M. I. Hoffert, Ocean carbon pumps: Analysis of relative strengths and efficiencies in ocean driven atmospheric CO_2 changes, in The Carbon Cycle and Atmospheric CO_2: Natural variations Archaean to present, ed. by E.T. Sundquist and W.S. Broecker, Geophys. Monogr. Ser., 32, 99-110, AGU, Washington, D.C. (1985)*

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:

- *Sarmiento, J. L. & Toggweiler, J. R., A new model for the role of the oceans in determining atmospheric pCO_2. Nature 308, 621–624 (1984)*
- *Siegenthaler, U. & Wenk, T. Rapid atmospheric CO_2 variations and ocean circulation. Nature 308, 624–626 (1984)*
- *Knox, F. & McElroy, M. Changes in atmospheric CO_2 influence of the marine biota at high latitude. J. Geopys. Res. 89, 4629–4637 (1984)*

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 CO_2 in the atmosphere. This early research led to two important ideas: high latitude regions are more important in determining atmospheric $p\mathrm{CO}_2$ than low latitudes, despite their much smaller area, and nutrient utilization and atmospheric $p\mathrm{CO}_2$ are tightly linked. Stronger nutrient utilization, especially in high latitudes, increases the efficiency of the carbon pump and lowers atmospheric $p\mathrm{CO}_2$.

- *Gruber, N. and J. L. Sarmiento, Large-scale biogeochemical-physical interactions in elemental cycles, in The Sea, edited by A.R. Robinson et al., pp. 337-399, John Wiley & Sons, Inc., New York (2002).*

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 CO_2 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.

- *Marinov, I., A. Gnanadesikan, J. R. Toggweiler and J. L. Sarmiento, The Southern Ocean Biogeochemical Divide, Nature {441}, 964--967, doi:10.1038, (2006).*

This paper shows that atmospheric CO_2 and global biological export production are controlled by separate regions of the Southern Ocean. Atmospheric $p\mathrm{CO}_2$ 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 $p\mathrm{CO}_2$ or global biological production) without greatly altering the other.

- *Toggweiler, J. R., R. Murnane, S. Carson, A. Gnanadesikan, and J. L. Sarmiento (2003), Representation of the carbon cycle in box models and GCMs - Part 2 Organic pump, Glob. Biogeochem. Cycles, 17(1), 1027, doi:10.1029/2001GB001841 (2003).*

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 $p\mathrm{CO}_2$ 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.

- *Ito, T., and M. J. Follows, Preformed phosphate, soft tissue pump and atmospheric CO_2, J. Marine Res., 63(4), 813--839, DOI: 10.1357/0022240054663231 (2005).*
- *Marinov, I., M. J. Follows, A. Gnanadesikan, J. L. Sarmiento, and R. D. Slater, How does ocean biology affect atmospheric pCO_2? Theory and models, Journal of Geophysical Research C: Oceans, 113, (2008a).*

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 $p\mathrm{CO}_2$.

- *Marinov, I., A. Gnanadesikan, J. L. Sarmiento, J. R. Toggweiler, M. Follows, and B. K. Mignone: Impact of oceanic circulation on biological carbon storage in the ocean and atmospheric pCO_2, Global Biogeochem. Cycles, 22, doi:10.1029/2007GB002958, (2008b).*

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 $p\mathrm{CO}_2$, 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:

- *Sigman DM; Boyle EA, Glacial/interglacial variations in atmospheric carbon dioxide, Nature 407, 6806, p: 859-869, doi: 10.1038/35038000, 2000*

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.

· *Ridgwell, A., and R. E. Zeebe, The role of the global carbonate cycle in the regulation and evolution of the Earth system, Earth Planet. Sci. Lett., 234, 299–315, doi:10.1016/j.epsl.2005.03.006, (2005)*

Some recent papers:

· *Archer, D., The fate of fossil fuel in geologic time, J. Geophys. Res., 110, C09S05, doi:10.1029/2004JC002625 (2005)*

· *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 $p\mathrm{CO}_2$ will evolve, for given CO_2 emissions and assuming equilibrium of ocean CO_2 with the atmosphere. The MIT GCM predicts that future carbon emissions must be restricted to a total of 700 GtC to achieve $p\mathrm{CO}_2$ stabilization at present-day transient levels.

· *Goodwin, P., M. J. Follows, and R. G. Williams, Analytical relationships between atmospheric carbon dioxide, carbon emissions, and ocean processes, Global Biogeochem. Cycles, 22, GB3030, doi:10.1029/2008GB003184, (2008)*
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 $p\mathrm{CO}_2$.

· *Kwon Eun Young; Sarmiento Jorge L.; Toggweiler J. R.; et al. The control of atmospheric* $p\mathrm{CO}_2$ *by ocean ventilation change: The effect of the oceanic storage of biogenic carbon, GBC 25, GB3026, doi:10.1029/2011GB004059, (2011).*
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 $p\mathrm{CO}_2$ to changes in ocean circulation is rather modest because ~30% of the change in atmospheric $p\mathrm{CO}_2$ 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 $p\mathrm{CO}_2$ 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.

- *Bacastow, R.B., The effect of temperature change of the warm surface waters of the oceans on atmospheric CO2, Global Biogeochem. Cycles, 10(2), 319-334, 10.1029/96GBO0039 (1996).*
- *Broecker, W., J. Lynch-Stieglitz, D. Archer, M. Hoffmann, E. Maier-Reimer, O. Marchal, T. Stocker, and N. Gruber, How strong is the Harvardton-Bear constraint?, Global Biogeochem. Cycles, 13, 817–821, (1999).*

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).

- *Toggweiler, J. R., A. Gnanadesikan, S. Carson, R. Murnane, and J. L. Sarmiento, Representation of the carbon cycle in box models and GCMs: 1. Solubility pump, Global Biogeochem. Cycles, 17(1), 1026, doi:10.1029/2001GB001401 (2003b)*

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., R. G. Williams and J. C. Marshall. 1996. The solubility pump in the subtropical gyre of the North Atlantic. J. Mar. Res., 54, 605– 630.*
- *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 CO_2, 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.

· *Schmittner, A., E. J. Brook, and J. Ahn (2007), Impact of the ocean's overturning circulation on atmospheric* CO_2*, in Ocean Circulation: Mechanisms and Impacts, edited by A. Schmittner, J. Chiang, and S. Hemming, pp. 315–334, AGU, Washington, D. C.*

· *Goodwin, P., and T. M. Lenton, Quantifying the feedback between ocean heating and* CO_2 *solubility as an equivalent carbon emission, Geophys. Res. Lett., 36, L15609, doi:10.1029/2009GL039247 (2009)*
Develops a theoretical method to quantify the feedback between ocean heating and the solubility of CO_2, for transient climate change.

· *DeVries, T., and F. Primeau, Atmospheric* pCO_2 *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 pCO_2 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 CO_2 in the ocean is in equilibrium with CO_2 in the atmosphere. Theory + models suggest that atmospheric pCO_2 depends approximately exponentially on the average ocean temperature. The current ocean-atmosphere system appears to have an exponential dependence of pCO_2 on global mean ocean alkalinity, but at slightly higher alkalinities, 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 CO_2 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 CO_2 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.*

· *Lovenduski, N. S., N. Gruber, S. C. Doney, and I. D. Lima, Enhanced* CO_2 *outgassing in the Southern Ocean from a positive phase of the Southern Annular Mode, Global Biogeochem. Cycles, 21, GB2026, doi:10.1029/2006GB002900 (2007). Modeling paper.*

· *Le Quere´, C., et al. (2007), Saturation of the Southern Ocean CO2 sink due to recent climate change, Science, 316, 1735–1738, doi:10.1126/ science.1136188. Observations + inverse model.*

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 CO_2 levels) and the ocean biological pump (this is the mechanism proposed by Toggweiler et al. 2006).

• Toggweiler J. R., Shifting Westerlies , Science 323 (5920), p.1434-1435, doi: 10.1126/science.1169823, (2009).

· Le Quéré, C., T. Takahashi, E. T. Buitenhuis, C. Rödenbeck, and S. C. Sutherland (2010), Impact of climate change and variability on the global oceanic sink of CO_2, Global Biogeochem. Cycles, 24, GB4007, doi:10.1029/2009GB003599.
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 CO_2. Climate change reduced the CO_2 uptake by 12% compared to a simulation where constant climate is imposed, and offset 63% of the trend in response to increasing atmospheric CO_2 alone. The response is caused by changes in wind patterns and ocean warming, with important nonlinear effects that amplify the response of oceanic CO_2 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.

· Sarmiento, J. L., T. M. C. Hughes, R. J. Stouffer, and S. Manabe: Simulated response of the ocean carbon cycle to anthropogenic climate warming. Nature, 393, 245–249 (1998).
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.

· Matear, R. J., and A. C. Hirst (1999), Climate change feedbacks on the future oceanic CO_2 uptake, Tellus, Ser. B, 51, 722–733.
Detailed modeling study of three feedbacks associated with the oceanic uptake of CO_2 under a warming climate: (i) warmer sea-surface temperature increased CO_2 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 CO_2 uptake by 41 Gt C, (iii) altered "natural" cycling of carbon in the ocean increased the cumulative ocean CO_2 uptake by 33 Gt C.

· Joos F.; Plattner G.K.; Stocker T.F.; et al., Global warming and marine carbon cycle feedbacks an future atmospheric CO2, Science 284 (5413),p.464-467, doi:10.1126/science.284.5413.464, (1999).

Modeling study that claims that future projected changes in the marine carbon cycle will have a modest impact on atmospheric CO_2. Sea surface warming decreases the oceanic carbon uptake (decreasing the solubility pump), increasing atmospheric CO_2 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).

· *Cox PM, Betts RA, Jones CD, Spall SA, Totterdell IJ (2000), Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model. Nature 408(6809):184–187. doi: 10.1038/35041539*
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.

· *Plattner, G.-K., F. Joos, T. F. Stocker, and O. Marchal (2001), Feedback mechanisms and sensitivities of ocean carbon uptake under global warming, Tellus Ser. B, 53, 564–592, doi:10.1034/j.16000889.*
The uptake of atmospheric CO_2 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 CO_2 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 CO_2 uptake until year 2100.

· *Friedlingstein, L. Bopp, P. Ciais, J.-L. Dufresne, L. Fairhead, H. LeTreut, P. Monfray, and J. Orr. Positive feedback between future climate change and the carbon cycle. Geophys. Res. Lett., 28,1543–1546 (2001)*
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 CO_2, respectively by 54% and 35% at 4 x CO_2.

· *Friedlingstein, P., J. L. Dufresne, P. M. Cox, and P. Rayner: How positive is the feedback between climate change and the carbon cycle? Tellus, 55B, 692–700, (2003).*
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 CO_2 and (2) vegetation and soil carbon response to global warming, with the latter dominating the difference between the Hadley and IPSL models.

· *Fung IY, Doney SC, Lindsay K, John J, Evolution of carbon sinks in a changing climate. Proc Natl Acad Sci 102(32), p. 11201–11206. doi:10.1073/pnas.0504949102, (2005).*
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 CO_2 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 CO_2 and amplify the climate change itself.

· *Friedlingstein P, Cox P, Betts R, Bopp L, et al., Climate-carbon cycle feedback analysis: results from the C4MIP model intercomparison. J Clim 19(14), p. 3337–3353. doi:10.1175/JCLI3800.1 (2006).*
Presents results of eleven coupled climate-carbon models forced with SRES A2 emission of CO_2 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). CO_2 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 CO_2 in the atmosphere is larger by 50-100ppm if climate change is accounted for, resulting in additional climate warming of 0.1°-1.5°C.

· Plattner, G.-K., and Coauthors: Long-term climate commitments projected with climate–carbon cycle models. J. Climate, 21, 2721–2751, (2008).
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 CO_2 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 CO_2 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!

· Schmittner, A., A. Oschlies, H. D. Matthews, and E. D. Galbraith, Future changes in climate, ocean circulation, ecosystems, and biogeochemical cycling simulated for a business-as-usual CO2 emission scenario until year 4000 AD, Global Biogeochem. Cycles, 22, GB1013, doi:10.1029/2007GB002953. (2008).

· Gregory, J. M., C. D. Jones, P. Cadule, and P. Friedlingstein, Quantifying carbon-cycle feedbacks, J. Clim., doi:10.1175/2009JCLI2949.1 (2009).
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 CO_2 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

· Sarmiento, J. L., and N. Gruber, Ocean Biogeochemical Dynamics, Chap. 8, Carbon cycle, pp. 318– 358, Princeton Univ. Press, Princeton, N. J. (2006),
Textbook contains an excellent introduction to the carbon cycle. Ideal for teaching graduate level classes.

· Denman, K.L., G. Brasseur, A. Chidthaisong, P. Ciais, P.M. Cox, R.E. Dickinson, D. Hauglustaine, C. Heinze, E. Holland, D. Jacob, U. Lohmann, S Ramachandran, P.L. da Silva Dias, S.C. Wofsy and X. Zhang, 2007: Couplings Between Changes in the Climate System and Biogeochemistry. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
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.

· David Archer, Global Warming: Understanding the Forecast, by D. Archer. 2006, Wiley-Blackwell. (new edition due in 2011).
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.

· R. G. Williams and M.J. Follows, Ocean Dynamics and the Carbon Cycle, Principles and Mechanisms. Cambridge Univ. Press (2011).
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.