



People are currently mining millions of years' worth of stored photosynthetic carbon from the solid Earth and transferring it to the atmosphere where it is profoundly changing the chemistry, physics, and biology of the atmosphere, land, and

oceans. Exchanges with the oceans and land surface have been modified substantially, so that currently only about half of anthropogenic emissions remain in the atmosphere. These "carbon sinks" are poorly understood, contributing a great deal of uncertainty to future climate.

*We consider biogeochemical and transport processes in land ecosystems, the oceans, and atmosphere as well as anthropogenic emissions. We will conclude with a study of changes in carbon cycling in the past and future, including predictions by coupled Earth System Models.*

The class format consists of **two formal lectures per week**. Notes will be downloadable in advance from the website. Readings will be assigned each week from textbooks and the current scientific literature. A series of computational exercises will be assigned to develop understanding of the material.

**Course grade is the average of five computational exercises** that will be assigned periodically throughout the semester.

**Schedule of Topics by Week**

Dates	Notes	Readings
Week 1	Overview	Denning 2017; LeQuere 2013

**LAND**

Week 2	Photosynthesis & Biogeochemistry	Denning, Bonan, Schulze
Week 3	Eddy Covariance & Disturbances	Baldocchi, Beer
Week 4	Ecosystem Manipulations & FACE	Norby, Luo, Finzi, LeBauer
Week 5	Global Terrestrial Carbon	Running, Pan
Week 6	Fossil Fuels & Energy	Raupach

**OCEANS**

Week 7	The Physical Ocean	W&F, Sabine
Week 8	Carbonate Chemistry & Ocean Acidification	W&F, Feeley
Week 9	Marine Biology, Nutrients, & Circulation	Selections from W&F
Week 10	Paleocarbon and the Long Tail	Archer & Brovkin

**ATMOSPHERE**

Week 11	Observing Atmospheric CO <sub>2</sub>	O'Dell, Graven
Week 12	Atmospheric Transport & Inverse Modeling	Peters, Schuh
Week 13	Other Atmospheric Carbon Tracers	Ballantyne

**CLIMATE**

Week 14	Carbon-Climate Feedback	Friedlingstein, Thornton
Week 15	21st Century Carbon & Climate	Gregory, Arora

We will take an all-day field trip to a subalpine eddy-covariance flux tower in the Medicine Bow National Forest of Wyoming which is documenting the collapse of a subalpine forest due to spruce beetle infestation.

## Readings

## OVERVIEW

- Denning, A. S. (2017), Combustion to Concentration to Warming: What Do Climate Targets Mean for Emissions? Climate Change and the Global Carbon Cycle, in *Reference Module in Earth Systems and Environmental Sciences*, pp. 1–11, Elsevier.
- LeQuere, C. et al. (2013), The global carbon budget 1959–2011, *Earth Syst. Sci. Data*, 5(1), 165–185, doi:10.5194/essd-5-165-2013. (PDF)

## LAND

- Denning, S. (1993), Relating Surface Energy Budgets to the Biochemistry of Photosynthesis: A Review for Non-Biologists, unpublished manuscript. (PDF)
- Bonan, G. 2008. "Chapter 17: Leaf Photosynthesis." In: Gordon Bonan, *Ecological Climatology — Concepts and Applications*. Cambridge University Press. p 237-252. (PDF)
- Schulze, E.-D., 2002. "Carbon Turnover." In: E.D. Schulze, E. Beck, and K. Muller-Hohenstein, *Plant Ecology*. Springer. p. 427-438. (PDF)
- Luo, Y. Q., D. Hui, and D. Zhang (2006), Elevated CO<sub>2</sub> stimulates net accumulations of carbon and nitrogen in land ecosystems: a meta-analysis, *Ecology*, 87(1), 53–63.(PDF)
- Finzi, A. C., D. J. P. Moore, E. H. DeLucia, J. Lichter, K. S. Hofmockel, R. B. Jackson, H. S. Kim, R. Matamala, H. R. McCARTHY, and R. Oren (2006), Progressive nitrogen limitation of ecosystem processes under elevated CO<sub>2</sub> in a warm-temperate forest, *Ecology*, 87(1), 15–25. (PDF)
- LeBauer, D. S., and K. K. Treseder (2008), Nitrogen limitation of net primary productivity in terrestrial ecosystems is globally distributed, *Ecology*, 89(2), 371–379. (PDF)
- Norby, R. J., J. M. Warren, C. M. Iversen, B. E. Medlyn, and R. E. McMurtrie (2010), From the Cover: CO<sub>2</sub> enhancement of forest productivity constrained by limited nitrogen availability, *Proc.Nat. Acad. Sci*, 107(45), 19368–19373, doi:10.1073/pnas.1006463107. (PDF)
- Baldocchi, D. (2003), Assessing the eddy covariance technique for evaluating carbon dioxide exchange rates of ecosystems: past, present and future, *Global Change Biology*, 9(4), 479–492. (PDF)
- Beer, C. et al. (2010), Terrestrial Gross Carbon Dioxide Uptake: Global Distribution and Covariation with Climate, *Science*, 329(5993), 834–838, doi:10.1126/science.1184984. (PDF)
- Kurz, W. A., C. C. Dymond, G. Stinson, G. J. Rampley, E. T. Neilson, A. L. Carroll, T. Ebata, and L. Safranyik (2008), Mountain pine beetle and forest carbon feedback to climate change, *Nature*, 452(7190), 987–990, doi:10.1038/nature06777. (PDF)
- Pan, Y., J. M. Chen, R. A. Birdsey, K. McCullough, L. He, and F. Deng (2011a), Age structure and disturbance legacy of North American forests, *Biogeosciences*, 8(3), 715–732, doi:10.5194/bg-8-715-2011. (PDF)
- Shevliakova, E., S. W. Pacala, S. Malyshev, G. C. HURTT, P. C. D. Milly, J. P. Caspersen, L. T. Sentman, J. P. Fisk, C. Wirth, and C. Crevoisier (2009), Carbon cycling under 300 years of land use change: Importance of the secondary vegetation sink, *Global Biogeochem. Cycles*, 23(2), n/a–n/a, doi:10.1029/2007GB003176. (PDF)
- Pan, Y., R. A. Birdsey, J. Fang, R. A. Houghton, P. E. Kauppi, W. A. Kurz, O. L. Phillips, A. Shvidenko, S. L. Lewis, and J. G. Canadell (2011b), A large and persistent carbon sink in the world's forests, *SCIENCE*, 333(6045), 988–993. (PDF)
- Running, S. W., R. R. Nemani, F. A. Heinsch, M. Zhao, M. Reeves, and H. Hashimoto (2004), A continuous satellite-derived measure of global terrestrial primary production, *BioScience*, 54(6), 547–560. (PDF)
- RAUPACH, M. R., G. Marland, P. Ciais, C. Quere, J. G. Canadell, G. Klepper, and C. B. Field (2007), Global and regional drivers of accelerating CO<sub>2</sub> emissions, *Proceedings of the National Academy of Sciences*, 104(24), 10288. (PDF)
- US Department of Energy (2013). *Energy Outlook to 2040*. Energy Information Administration. (PDF)

## OCEAN

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- Feely, R. A., S. C. Doney, and S. R. Cooley (2009), Ocean acidification: present conditions and future changes in a high-CO<sub>2</sub> world, *Oceanography*, 22, 36–47. (PDF)
- Doney, S. C., V. J. Fabry, R. A. Feely, and J. A. Kleypas (2009), Ocean Acidification: The Other CO<sub>2</sub> Problem, *Annu. Rev. Marine. Sci.*, 1(1), 169–192, doi:10.1146/annurev.marine.010908.163834. (PDF)
- Williams, R. and M. Follows (2006). Ocean Dynamics and the Carbon Cycle, SELECTIONS including nutrient cycling and circulation. Oxford University Press. (PDF)
- Sabine, C. L., R. A. Feely, N. Gruber, R. M. Key, K. Lee, J. L. Bullister, R. Wanninkhof, C. Wong, D. W. R. Wallace, and B. Tilbrook (2004), The Oceanic Sink for Anthropogenic CO<sub>2</sub>, *Science*, 305(5682), 367–371, doi:10.1126/science.1097403. (PDF)
- Sarmiento, J. L., and N. Gruber (2006). Ocean Biogeochemical Dynamics. Chapter 8: The Carbon Cycle. Princeton University Press. (PDF)
- LeQuere, C. et al. (2007), Saturation of the Southern Ocean CO<sub>2</sub> Sink Due to Recent Climate Change, *Science*, 316(5832), 1735–1738, doi:10.1126/science.1136188. (PDF)
- Lovenduski, N. S., N. Gruber, and S. C. Doney (2008), Toward a mechanistic understanding of the decadal trends in the Southern Ocean carbon sink, *Global Biogeochem. Cycles*, 22(3), doi:10.1029/2007GB003139. (PDF)
- Archer, D., and V. Brovkin (2008), The millennial atmospheric lifetime of anthropogenic CO<sub>2</sub>, *Climatic Change*, 90(3), 283–297, doi:10.1007/s10584-008-9413-1. (PDF)

#### ATMOSPHERE

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- Peters, W., A. R. Jacobson, C. Sweeney, A. E. Andrews, T. J. Conway, K. A. Masarie, J. B. Miller, L. Bruhwiler, G. Petron, and A. Hirsch (2007), An atmospheric perspective on North American carbon dioxide exchange: CarbonTracker, *Proceedings of the National Academy of Sciences*, 104(48), 18925. (PDF)
- Schuh, A. E. et al. (2013), Evaluating atmospheric CO<sub>2</sub> inversions at multiple scales over a highly inventoried agricultural landscape, *Global Change Biology*, 19(5), 1424–1439, doi:10.1111/gcb.12141. (PDF)
- Chevallier, F., F.-M. Bréon, and P. J. Rayner (2007), Contribution of the Orbiting Carbon Observatory to the estimation of CO<sub>2</sub> sources and sinks: Theoretical study in a variational data assimilation framework, *J. Geophys. Res.*, 112(D9), doi:10.1029/2006JD007375. (PDF)
- Crisp, D. et al. (2012), The ACOS CO<sub>2</sub> retrieval algorithm &ndash; Part II: Global XCO<sub>2</sub> data characterization, *Atmos. Meas. Tech.*, 5(4), 687–707, doi:10.5194/amt-5-687-2012. (PDF)

#### CLIMATE

- Friedlingstein, P., P. M. Cox, R. A. Betts, L. Bopp, W. Von Bloh, V. Brovkin, P. Cadule, S. C. Doney, M. Eby, and I. Y. Fung (2006), Climate-carbon cycle feedback analysis: Results from the C4MIP model intercomparison, *J. Climate*, 19(14), 3337–3353. (PDF)
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- Gregory, J. M., C. D. Jones, P. Cadule, and P. Friedlingstein (2009), Quantifying Carbon Cycle Feedbacks, *J. Climate*, 22(19), 5232–5250, doi:10.1175/2009JCLI2949.1. (PDF)
- Arora, V. K., F. H. Chiew, and R. B. Grayson (2001), Effect of sub-grid-scale variability of soil moisture and precipitation intensity on surface runoff and streamflow, *Journal of Geophysical Research: Atmospheres* (1984–2012), 106(D15), 17073–17091. (PDF)

## ASSIGNMENTS

There will be five class projects over the course of the semester. Each assignment involves writing and using a simple computer program to do some calculations using simplified “toy” models of the carbon cycle to investigate processes in the real world.

You are welcome to work on these in groups or on your own. Use any programming language or environment you like. If you are new to programming I suggest a well-supported open-source modern environment supported on all platforms, like [Python](#), [R](#), or [Octave](#). If you’ve never written computer programs before, I suggest a [wonderful book by John Zelle](#) or the free [online programming course](#) provided by the Khan Academy. I have a few copies of the Zelle book to lend. I am happy to provide a lot of help with the programming projects outside of class time as well, because I think this is a very important part of the course.

All of the assignments are also linked to the [web-based toy models provided on the class website](#). The website provides all the code used to drive the web-based models. You are welcome to use the code on the website as a template, copy-paste it as much as you want, and check your answers against mine if you find that helpful.