16:460:613 -- Major Transitions in the Evolution of the Global Carbon Cycle
Rutgers Dept. of Earth & Planetary Sciences -- Spring 2012

Meets: Tuesdays, 9:30am-12:30pm, Wright 247

Instructors:

Professor Dennis Kent	Professor Robert Kopp
GSLB 101	Wright 225
dvk@rci.rutgers.edu	robert.kopp@rutgers.edu

This special topics course covers the evolution of the global carbon cycle over the 4.5 billion years of Earth's history, with a particular focus on the relationship between the carbon cycle and paleogeography.

Students will be expected to attend every class, to lead discussion of the week's paper on a rotating basis, and write a *Nature*-style critical review article related to the topic of the course that will be presented during the final week of the course. (The exact nature of the presentation will depend on enrollment, but we expect it to consist of roughly 15 minutes of prepared talk followed by 15 minutes of discussion.)

Grades will be based on participation throughout the term (25%), discussion leadership (50%), and the research project (25%).

Indicative Reading List
(Subject to change based on enrollment and interests)

Week 1: The Basics of the Long-Term Carbon Cycle
January 17, 2012

1. R Berner and K Maasch, "Chemical weathering and controls on atmospheric O_2 and CO_2: Fundamental principles were enunciated by J.J. Ebelmen in 1845," *Geochimica et Cosmochimica Acta* 60, no. 9 (May 1996): 1633-1637.
2. Berner, Robert A. "A model for atmospheric CO 2 over Phanerozoic time." *American Journal of Science* 291, no. 4 (April 1, 1991): 339 -376.

Highly suggested background: Holmén, Kim. "11 The global carbon cycle." In *Earth System Science From Biogeochemical Cycles to Global Change*, Volume 72:282-321. Academic Press, 2000.

GEOCARB updates to skim:
1. Berner, Robert A. "GEOCARB II; a revised model of atmospheric CO 2 over Phanerozoic time." *American Journal of Science* 294, no. 1 (January 1, 1994): 56 -91.
2. Berner, Robert A., and Zavareth Kothavala. "Geocarb III: A Revised Model of Atmospheric CO2 over Phanerozoic Time." *American Journal of Science* 301, no. 2 (February 2001): 182 -204.

Optional: Robert A. Berner, "A. G. Hoegbom and the development of the concept of the geochemical carbon cycle," *American Journal of Science* 295, no. 5 (May 1, 1995): 491 -495.

Week 2: Carbon Sources

January 24, 2012

The Gerlach paper provides summary of quantitative estimates of modern CO2 degassing; more details of arguably the best methodology can be found in the background readings Marty & Tolstikhin (i.e., scrutinize the abstract, read the Intro and scan the figures).

1. Gerlach, T., 2011, Volcanic Versus Anthropogenic Carbon Dioxide: Eos, Transactions, American Geophysical Union, v. 92, p. 201-202.

- *Background:* Marty, B., and I. N. Tolstikhin, 1998, CO2 fluxes from mid-ocean ridges, arcs and plumes: Chemical Geology, v. 145, p. 233-248.

The degassing curve in GEOCARB II is based on parameterized ocean-floor production variations for the past 180 Myr by Engebretson et al.

2. Engebretson, DC, KP Kelley, HJ Cashman, and MA Richards. "180 million years of subduction." *GSA today* 2, no. 5 (1992): 93–100.

For earlier models and earlier times in the other GECARB models, relative ocean floor production rates were obtained by an inversion of a sea-level curve by Gaffin whose paper you should peruse as a background reading. We will focus discussion on this topic with a forward model of sea-level by Kominz and a more recent paper by Muller et al.

3. Kominz, M. A., 1984, Oceanic ridge volumes and sea-level change: An error analysis, in J. Schler, ed., American Association of Petroleum Geology Memoir 36, p. 109-127.
4. Muller, R. D., M. Sdrolias, C. Gaina, B. Steinberger, and C. Heine, 2008, Long-term sea-level fluctuations driven by ocean basin dynamics: Science, v. 319, p. 1357-1362.

- Background: Gaffin, S., 1987, Ridge volume dependence on seafloor generation rate and inversion using long term sealevel change: American Journal of Science, v. 287, p. 596-611.

Contrasting perspectives on sea-floor production rate calculations are provided by Rowley, whose analysis suggests there have been no significant changes in ocean floor production rate, and by Cogné and Humler, who suggest varying ocean floor production rates but with a different pattern than conventionally assumed.

5. Rowley, D. B., 2002, Rate of plate creation and destruction: 180 Ma to present: Geological Society of America Bulletin, v. 114, p. 927-933.
6. Cogné, J. P., and E. Humler, 2006, Trends and rhythms in global seafloor generation rate: Geochemistry, Geophysics, Geosystems, v. 7, p. Q03011, doi:10.1029/2005GC001148.

Week 3: Carbon isotope records
January 31, 2012

Kump and Arthur develop a simple dynamic model for interpreting carbon isotope perturbations.

1. Lee R. Kump and Michael A. Arthur, "Interpreting carbon-isotope excursions: carbonates and organic matter," *Chemical Geology* 161, no. 1-3 (September 1999): 181-198.

Katz et al look at coupled $\delta^{13}C_{org}$ and $\delta^{13}C_{carb}$ records from the Mesozoic and Cenozoic, and place these records in the context of the supercontinent cycle and biological evolution.

2. Miriam E. Katz et al., "Biological overprint of the geological carbon cycle," *Marine Geology* 217, no. 3-4 (June 2005): 323-338.

Hayes and Waldbauer develop a model for looking at carbon isotope records in the context of changing global redox conditions.

3. John M Hayes and Jacob R Waldbauer, "The carbon cycle and associated redox processes through time," *Philosophical Transactions of the Royal Society B: Biological Sciences* 361, no. 1470 (June 29, 2006): 931 -950.

Schidolwski focuses on the biological processes underlying fractionation and what the carbon isotopic record can say about the history of life.

4. Manfred Schidlowski, "Carbon isotopes as biogeochemical recorders of life over 3.8 Ga of Earth history: evolution of a concept," *Precambrian Research* 106, no. 1-2 (February 2001): 117-134.

Week 4: Inorganic carbon sinks
February 7, 2012

1. James C. G. Walker, P. B. Hays, and J. F. Kasting, "A NEGATIVE FEEDBACK MECHANISM FOR THE LONG-TERM STABILIZATION OF EARTH'S SURFACE TEMPERATURE," *Journal of Geophysical Research* 86, no. 10 (n.d.): PP. 9776-9782.
2. Edmond, J. M. "Himalayan Tectonics, Weathering Processes, and the Strontium Isotope Record in Marine Limestones." *Science* 258, no. 5088 (December 4, 1992): 1594 -1597.
3. Misra, Sambuddha, and Philip N. Froelich. "Lithium Isotope History of Cenozoic Seawater: Changes in Silicate Weathering and Reverse Weathering." *Science* (January 26, 2012). http://www.sciencemag.org/content/early/2012/01/25/science.1214697.abstract.
4. M. E. Raymo and W. F. Ruddiman, "Tectonic forcing of late Cenozoic climate," *Nature* 359, no. 6391 (1992): 117-122.
5. Dennis V. Kent and Giovanni Muttoni, "Equatorial convergence of India and early Cenozoic climate trends," *Proceedings of the National Academy of Sciences* 105, no. 42 (October 21, 2008): 16065 -16070.

Week 5: The Archean biosphere and greenhouse records
February 14, 2012

** *TERM PAPER TOPIC SELECTION DUE* **

Walker and Sleep & Bird look at Archean ecology.

1. Walker, James C. G. "Was the Archaean biosphere upside down?" *Nature* 329, no. 6141 (October 22, 1987): 710-712.
2. Sleep, Norman H, and Dennis K Bird. "Evolutionary Ecology During the Rise of Dioxygen in the Earth's Atmosphere." *Philosophical Transactions of the Royal Society B: Biological Sciences* 363, no. 1504 (2008): 2651 -2664.

Kasting employs the Walker et al. framework to look at the Faint Young Sun question.

3. J F Kasting, “Long-term stability of the Earth’s climate,” *Global and Planetary Change* 75 (1989): 83-95.

In Haqq-Misra et al., focus on Intro, Results, Discussion, Conclusions and figures .

4. Jacob D. Haqq-Misra et al., “A Revised, Hazy Methane Greenhouse for the Archean Earth,” *Astrobiology* 8, no. 6 (December 2008): 1127-1137.

Three short *Nature* papers attempt to place constraints on Archean carbon dioxide:

5. Rye, Rob, Phillip H. Kuo, and Heinrich D. Holland. “Atmospheric Carbon Dioxide Concentrations Before 2.2 Billion Years Ago.” *Nature* 378, no. 6557 (December 7, 1995): 603-605.
6. Hessler, Angela M., Donald R. Lowe, Robert L. Jones, and Dennis K. Bird. “A Lower Limit for Atmospheric Carbon Dioxide Levels 3.2 Billion Years Ago.” *Nature* 428, no. 6984 (April 15, 2004): 736-738.
7. Minik T. Rosing et al., “No climate paradox under the faint early Sun,” *Nature* 464, no. 7289 (April 1, 2010): 744-747.

Week 6: The Archean-Paleoproterozoic Transition
February 21, 2012

1. S. M. Reddy and D. A. D. Evans, “Palaeoproterozoic supercontinents and global evolution: correlations from core to atmosphere,” *Geological Society, London, Special Publications* 323, no. 1 (January 1, 2009): 1 -26.
2. Robert E. Kopp et al., “The Paleoproterozoic snowball Earth: A climate disaster triggered by the evolution of oxygenic photosynthesis,” *Proceedings of the National Academy of Sciences of the United States of America* 102, no. 32 (2005): 11131 -11136.

Week 7: IITPW and Paleomagnetic Reconstructions
February 28, 2012

*** TERM PAPER INITIAL OUTLINE AND REFERENCES LIST DUE ***

Evans and Pisarevsky will provide an intro to apparent polar wander and bring us up to date on a topic touched on in week 6, namely how we know (or not) about Precambrian supercontinents.

1. Evans, D. A. D., and S. A. Pisarevsky, 2008, Plate tectonics on early Earth? Weighing the paleomagnetic evidence: Geological Society of America Special Papers, v. 440, p. 249-263.

Raub et al. provide an overview of true polar wander, and why we care about it in a course on the evolution of the carbon cycle.

2. TD Raub, JL Kirschvink, and DAD Evans, “True polar wander: Linking deep and shallow geodynamics to hydro-and bio-spheric hypotheses,” *Treatise on Geophysics* 5 (2007): 565–589.

Kirschvink et al. describe paleomagnetic evidence for Ediacaran-early Cambrian inertial interchange true polar wander.

3. Kirschvink, Joseph L, Robert L Ripperdan, and David A Evans. "Evidence for a Large-Scale Reorganization of Early Cambrian Continental Masses by Inertial Interchange True Polar Wander." *Science* 277, no. 5325 (July 25, 1997): 541–545.

A brand new paper by Mitchell et al. uses TPW and its relationship to the supercontinent cycle to generate reconstructions of Nuna and Rodinia constrained in paleolongitude.

4. Mitchell, Ross N., Taylor M. Kilian, and David A. D. Evans. "Supercontinent Cycles and the Calculation of Absolute Palaeolongitude in Deep Time." *Nature* 482, no. 7384 (February 9, 2012): 208-211.

Week 8: Snowball Earth
March 6, 2012

Hoffman and Schrag offer a seminal review of the snowball Earth hypothesis, which will be the focus of the class.

1. Paul F Hoffman and Daniel P Schrag, "The snowball Earth hypothesis: testing the limits of global change," *Terra Nova* 14, no. 3 (June 1, 2002): 129-155.

Mills et al. argue the pacing of Snowball events was set by limitations on silicate weathering rates.

2. Benjamin Mills et al., "Timing of Neoproterozoic glaciations linked to transport-limited global weathering," *Nature Geosci* 4, no. 12 (December 2011): 861-864.

Nick Swanson-Hysell and his colleagues argue the Sturtian snowball Earth event (~720 Ma) played a key role in the development of a distinctive, long-lived dissolved organic carbon pool that characterizes the late Neoproterozoic.

3. Nicholas L. Swanson-Hysell et al., "Cryogenian Glaciation and the Onset of Carbon-Isotope Decoupling," *Science* 328, no. 5978 (April 30, 2010): 608 -611.

We will not discuss in detail due to time, but Sansjofre et al. offer a critical view on the Snowball hypothesis.

4. P. Sansjofre et al., "A carbon isotope challenge to the snowball Earth," *Nature* 478, no. 7367 (October 6, 2011): 93-96.

Week 9: Phanerozoic Carbon Dioxide Records
March 20, 2012

We will begin with Royer et al.'s review of multiple Phanerozoic CO_2 proxies.

1. Royer, D.L., R.A. Berner, I.P. Montañez, N.J. Tabor, and D.J. Beerling. 2004. "CO_2 as a Primary Driver of Phanerozoic Climate." *GSA Today* 14 (3): 4–10.

Breecker et al. provide a reconstruction based on the carbon isotopic composition of soil carbonates.

2. D. O. Breecker, Z. D. Sharp, and L. D. McFadden, "Atmospheric CO2 concentrations during ancient greenhouse climates were similar to those predicted for A.D. 2100," *Proceedings of the National Academy of Sciences* 107, no. 2 (January 12, 2010): 576 -580.

Beerling et al. use the stomatal index of fossil leaves.

3. David J. Beerling, Andrew Fox, and Clive W. Anderson, "Quantitative uncertainty analyses of ancient atmospheric CO2 estimates from fossil leaves," *American Journal of Science* 309, no. 9 (November 2009): 775 -787.

Pagani develops the alkenone $\delta^{13}C$ CO_2 proxy.

4. Pagani, Mark. 2002. "The alkenone-CO2 Proxy and Ancient Atmospheric Carbon Dioxide." *Philosophical Transactions of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences* 360 (1793) (April 15): 609 –632. doi:10.1098/rsta.2001.0959.

The Beerling et al. and Pagani papers are both a bit of a slog. Try not to get too lost in the details with these, and instead focus on understanding the basic principles underlying these proxies.

Week 10: The Permo-Triassic Extinction
March 27, 2012

1. Hönisch, Bärbel, Andy Ridgwell, Daniela N Schmidt, Ellen Thomas, Samantha J Gibbs, Appy Sluijs, Richard Zeebe, et al. 2012. "The Geological Record of Ocean Acidification." *Science* 335 (6072) (March 2): 1058–1063. doi:10.1126/science.1208277.
2. Payne, Jonathan L, Alexandra V Turchyn, Adina Paytan, Donald J DePaolo, Daniel J Lehrmann, Meiyi Yu, and Jiayong Wei. 2010. "Calcium Isotope Constraints on the End-Permian Mass Extinction." *Proceedings of the National Academy of Sciences* 107 (19) (May 11): 8543–8548. doi:10.1073/pnas.0914065107.
3. Kump, Lee R, Alexander Pavlov, and Michael A Arthur. 2005. "Massive Release of Hydrogen Sulfide to the Surface Ocean and Atmosphere During Intervals of Oceanic Anoxia." *Geology* 33 (5) (May 1): 397–400. doi:10.1130/G21295.1.
4. Svensen, Henrik, Sverre Planke, Alexander G. Polozov, Norbert Schmidbauer, Fernando Corfu, Yuri Y. Podladchikov, and Bjørn Jamtveit. 2009. "Siberian Gas Venting and the end-Permian Environmental Crisis." *Earth and Planetary Science Letters* 277 (3–4) (January 30): 490–500. doi:10.1016/j.epsl.2008.11.015.

Week 11: The Paleocene-Eocene Thermal Maximum
April 3, 2012

1. Francesca A. McInerney and Scott L. Wing, "The Paleocene-Eocene Thermal Maximum: A Perturbation of Carbon Cycle, Climate, and Biosphere with Implications for the Future," *Annual Review of Earth and Planetary Sciences* 39, no. 1 (May 30, 2011): 489-516.
2. Koch, Paul L., James C. Zachos, and Philip D. Gingerich. 1992. "Correlation Between Isotope Records in Marine and Continental Carbon Reservoirs Near the Palaeocene/Eocene Boundary." *, Published Online: 23 July 1992; | Doi:10.1038/358319a0* 358 (6384) (July 23): 319–322. doi:10.1038/358319a0.
3. Kennett, J. P., and L. D. Stott. 1991. "Abrupt Deep-sea Warming, Palaeoceanographic Changes and Benthic Extinctions at the End of the Palaeocene." *, Published Online: 19 September 1991; | Doi:10.1038/353225a0* 353 (6341) (September 19): 225–229. doi:10.1038/353225a0.

4. Murphy, B.H., K.A. Farley, and J.C. Zachos. 2010. "An Extraterrestrial 3He-based Timescale for the Paleocene–Eocene Thermal Maximum (PETM) from Walvis Ridge, IODP Site 1266." *Geochimica Et Cosmochimica Acta* 74 (17) (September 1): 5098–5108. doi:10.1016/j.gca.2010.03.039.
5. Higgins, John A., and Daniel P. Schrag. 2006. "Beyond Methane: Towards a Theory for the Paleocene-Eocene Thermal Maximum." *Earth and Planetary Science Letters* 245: 523–537.

Week 12: An Early Anthropocene?
April 10, 2012

Zalasiewicz et al. offer a definition for the Anthropocene and discuss how human civilization has affected the geological record.

1. Zalasiewicz, J. et al. "Are We Now Living in the Anthropocene?" *GSA Today* 18 (2): 5.

Ruddiman (2003) presents the hypothesis that anthropogenic carbon dioxide and methane emissions have played a critical role in the climate history of the last 8,000 years.

2. Ruddiman, William F. 2003. "The Anthropogenic Greenhouse Era Began Thousands of Years Ago." *Climatic Change* 61 (3) (December 1): 261–293. doi:10.1023/B:CLIM.0000004577.17928.fa.

Broecker and Stocker counter, contending that Ruddiman's reasoning by analogy to previous interglacials is faulty and that the Holocene carbon isotope record is inconsistent with a CO_2 release of the necessary magnitude. Elsig et al. provide a more up-to-date Holocene carbon isotope record and place a more quantitative constraint on land-biosphere carbon transfer. In reading Elsig et al., please focus on elements relevant to the Ruddiman hypothesis and Brocker and Stocker's claims.

3. Wallace S. Broecker and Thomas F. Stocker, 2006, "The Holocene CO2 rise: Anthropogenic or natural?," *Eos* 87, no. 3: PAGE 27.
4. Elsig, Joachim, Jochen Schmitt, Daiana Leuenberger, Robert Schneider, Marc Eyer, Markus Leuenberger, Fortunat Joos, Hubertus Fischer, and Thomas F. Stocker. 2009. "Stable Isotope Constraints on Holocene Carbon Cycle Changes from an Antarctic Ice Core." *Nature* 461 (7263) (September 24): 507–510. doi:10.1038/nature08393.

Ruddiman et al. respond.

5. Ruddiman, W. F, J. E Kutzbach, and S. J Vavrus. 2011. "Can Natural or Anthropogenic Explanations of Late-Holocene CO2 and CH4 Increases Be Falsified?" *The Holocene* 21 (5) (August 1): 865–879. doi:10.1177/0959683610387172.

Week 13: The Future Carbon Cycle
April 17, 2012

1. Solomon, Susan, Gian-Kasper Plattner, Reto Knutti, and Pierre Friedlingstein. 2009. "Irreversible Climate Change Due to Carbon Dioxide Emissions." *Proceedings of the National Academy of Sciences* 106 (6) (February 10): 1704–1709. doi:10.1073/pnas.0812721106.

2. David Archer and Andrey Ganopolski, “A movable trigger: Fossil fuel CO2 and the onset of the next glaciation,” *Geochemistry Geophysics Geosystems* 6 (May 5, 2005): Q05003.
3. King-Fai Li et al., “Atmospheric pressure as a natural climate regulator for a terrestrial planet with a biosphere,” *Proceedings of the National Academy of Sciences* 106, no. 24 (June 16, 2009): 9576 -9579.

Week 14: Student research project presentations

Each student should be prepared to give a 10-15 minute presentation of her/his term project, followed by about 15 minutes of discussion.