

Global Climate Change

GC61A MCC: 133 Saturday 0830h

Carbon Cycle and Climate: Past, Present, and Future I (joint with A, B, H, OS, PP)

Presiding: N Zeng, University of Maryland; M Heiman, Max-Planck-Institut fuer Biogeochemie; N Gruber, University of California, Los Angeles; T Crowley, Duke University

GC61A-01 0830h

A Volcanic End to Terminal Neoproterozoic Glaciation?

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Field observations and newly acquired carbon and sulfur isotope evidence from carbonates atop diamictites of the Fauquier Formation, and equivalents, in northern Virginia yield valuable insights into global environments during the evolution of Ediacaran-grade animals, and the termination of the youngest Neoproterozoic ice age. The transgressive succession of diamictite, sandstone, siltstone, and organic-rich carbonate in the Fauquier Formation was deposited in a rift environment between 702-705 Ma, the age of underlying Robertson River rhyolites, and 564 +/- 9 Ma, the age of overlying Catoclin Formation flood basalts. A strong negative-to-positive $\delta^{13}\text{C}$ trend (from -5‰ at the base to $+3\text{‰}$ at the top of the composite section) is recognized in the carbonates, which is typical of post-glacial Neoproterozoic cap carbonates worldwide, supporting earlier claims that the diamictite at the base of the unit is glacial in origin. A significant enrichment of ^{13}C in co-existing organic matter suggests carbon limitation associated with photosynthetic blooms in the aftermath of the Fauquier ice age. This cap carbonate is also unique insofar as its uppermost beds are inter-layered with lava flows of the Catoclin Formation. The Catoclin is a regionally extensive unit associated with large scale rifting from Southern Virginia to Newfoundland. Carbonate sedimentation and igneous activity were clearly contemporaneous, as the soft Fauquier sediments were deformed and altered by the lavas. This intimate sedimentary and igneous association suggests that the end of the ice age may have been forced by a sudden increase in greenhouse capacity caused by volcanic degassing of CO_2 . In addition, the radiometric determination is the best-known constraint for the age of the post-glacial carbonate and the conformable diamictite beneath, thereby providing an upper bound for Neoproterozoic glaciation. Notably, an ash layer in Newfoundland interbedded with a diverse assemblage of complex Ediacaran fossils is also around 565 Ma. If related to the same rift related igneous province, the observations made in northern Virginia suggest that environmental changes in the immediate aftermath of terminal Neoproterozoic glaciation, and the radiation of macroscopic animals, are causally linked.

GC61A-02 0845h INVITED

The geologic carbon cycle and the evolution of atmospheric carbon dioxide

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CO_2 is supplied to the atmosphere by metamorphic reactions involving carbonate minerals and by mantle degassing. CO_2 is consumed from the atmosphere by silicate rock weathering and subsequent carbonate mineral sedimentation. Photosynthetic production of organic carbon also consumes atmospheric CO_2 , whereas oxidation of organic matter returns CO_2 to the atmosphere. The balance between these carbon flows largely determines atmospheric CO_2 content on million year

and longer time scales. This long-term, or geological, carbon cycle is distinguished from the more familiar short-term cycle involving the transfer of carbon between the oceans, atmosphere, living biosphere and soils.

A typical molecule of volcanic CO_2 remains in the atmosphere and ocean roughly 100,000 years before being buried as carbonate sediments, yet atmospheric CO_2 content has not varied widely for many millions of years. The stability of atmospheric CO_2 content over many residence times of CO_2 in the atmosphere suggests that a strong negative feedback exists to stabilize atmospheric CO_2 content. For a negative feedback to exist, either sources or sinks of CO_2 to the atmosphere must be influenced by atmospheric CO_2 content.

Silicate rock weathering (and subsequent carbonate mineral sedimentation) consumes atmospheric CO_2 and can be shown to increase with increasing temperature and atmospheric CO_2 content. Enhanced atmospheric CO_2 concentration, through the CO_2 -greenhouse effect, would tend to warm the land and increase the hydrologic cycle with more water contacting silicate minerals. Both of these processes would function as a negative feedback stabilizing atmospheric CO_2 concentration through accelerated silicate rock-weathering.

The evolution of Earth's biota has had a very large impact on silicate weathering rates, and hence atmospheric CO_2 . In general, land plants tend to accelerate silicate rock weathering, lowering atmospheric CO_2 levels.

In this talk, we will show that many factors may have influenced the evolution of atmospheric CO_2 content. A model of the long term carbon cycle, GEO-CARB, has been constructed that quantitatively considers: (1) the uplift of mountains as they affect relief, climate and silicate weatherability, (2) the rise of large vascular land plants as they affect both silicate weathering and organic carbon burial; (3) changes in continental size and position as they affect temperature and river runoff from the continents; (4) variations of atmospheric CO_2 as they affect weathering as a negative feedback mechanism; (5) the slow evolution of the sun as it affects global warming. Factors affecting degassing include changes in the distribution of carbonates between shallow platforms and the deep sea as they affect the amount of carbonate undergoing thermal decomposition via subduction of ocean floor. Sensitivity analysis shows that the major forcing factors affecting CO_2 over the Phanerozoic (past 550 million years) are plant evolution, solar evolution, and mountain uplift. Levels of paleo- CO_2 calculated via GEO-CARB are, within the errors of the method, in good agreement with many independent estimates using a variety of paleobiological and geochemical methods. The Phanerozoic CO_2 trend is in agreement with the atmospheric greenhouse effect as a major control on (very) long-term climate.

GC61A-03 0905h INVITED

Control of Atmospheric CO_2 and Climate over the Phanerozoic

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The geochemical and paleobiological records from sediments document a spectacular climate transition from the persistent warm climates of the Cretaceous and early Cenozoic to the cold, semi-glaciated climates of the Plio-Pleistocene. Climate reconstructions for the earlier Mesozoic and Paleozoic are less precise, but quasi-periodic oscillations between warm, ice-free climates, such as the Silurian and Devonian, and partly glaciated climates, such as the Ordovician and Permian, appear to be a general feature of the entire Phanerozoic. I present a new theory to explain this general pattern of long term climate change focusing on changes in the rate of volcanic outgassing and metamorphic release of CO_2 . Previous studies have estimated the outgassing rate from changes in the average rate of sea floor spreading, as this controls both the rate of mid-ocean ridge volcanism and the rate of subduction. This, in turn, is calculated from the Phanerozoic eustatic sea level curve. A re-examination of the modern rate of volcanic outgassing as well as estimates of the calcium carbonate budget suggest that the sea floor spreading rate is likely a poor proxy for volcanic outgassing rate through time. In the modern ocean, more than 10 times as much calcium carbonate is being buried as is being subducted. This severe imbalance cannot be maintained over the Phanerozoic. An alternative explanation is explored that considers the site of calcium carbonate deposition and the quasi-periodic destruction of ocean basins. The warmth of the Cretaceous is explained by subduction of the carbonate-rich Tethys, which ended in the Eocene when Cenozoic cooling commenced. The current cool climate will remain until the carbonate-rich Atlantic is subducted. A natural oscillation is proposed to explain the quasi-periodic pattern of climate change over the Phanerozoic.

GC61A-04 0925h

Impact of the Himalayan Orogeny on Global Climate

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The hypothesis that orogeny and the consequent uplift and erosion of continental crust cause global cooling by changing the feedback between temperature and silicate chemical weathering rate is longstanding but unresolved. Testing this hypothesis is frustrated by the difficulty of distinguishing the contributions of carbonate and silicate sources to riverine chemical fluxes and determining the importance of erosion rate on chemical weathering fluxes. Potential CO_2 degassing by decarbonation reactions during collisional orogens further complicates prediction of their climatic consequences.

Calculation of the silicate-derived fluxes in the major rivers draining the Himalayas and Tibet implies that this region contributes between 16 and 33 % of the global silicate weathering flux from 4.5 % of land area. Silicates are weathering at a factor of 3 to 10 faster in the Himalayan-Tibetan region than average continental crust. This is consistent with some, but by no means all, interpretations of the impact of erosion on silicate weathering rates. Such an increase in "weatherability" of the continental crust might cool global climate by between 1 and 6° C for various temperature-weathering rate dependencies.

However this simple interpretation of global climate change over the Cenozoic is complicated by interpretations of the seawater Sr-isotope curve which imply a net increase in solid-earth CO_2 degassing since 40 Ma. Allowing for the impact of weathering of high $^{87}\text{Sr}/^{86}\text{Sr}$ rocks exposed by the Himalayan orogeny, the riverine Sr flux must have increased by about 60 % over this time period. Alternative explanations, that the change in seawater $^{87}\text{Sr}/^{86}\text{Sr}$ ratios reflect only the changing $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of the riverine input lead to an equivalent conclusion. The mean river $^{87}\text{Sr}/^{86}\text{Sr}$ ratio would need to be as low as 0.7095 at 40 Ma, a value which would anyway imply that rates of silicate weathering had fallen significantly. If the increased riverine Sr flux is assumed to reflect increased silicate chemical weathering and thus increased solid-Earth CO_2 degassing then this offsets much, if not all, of the net cooling attributed to increased erosion in the Himalayan-Tibetan region. Fortunately for all the hypotheses, the combined uncertainties permit a wide range of solutions!

GC61A-05 0940h

Were CO_2 levels and climate coupled during the middle Miocene climatic optimum?

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The middle Miocene climatic optimum was a transient warming event 16 Ma before present. Recent workers have cited isotopic (Pearson and Palmer, 2000, Nature 406:695) and stomatal index (Royer et al., 2001, Science 292:2310) evidence to suggest that this climatic warming occurred without a significant increase in atmospheric pCO_2 from near-modern levels, and that CO_2 levels were decoupled from climatic change. The Picture Gorge Subgroup, of the Columbia River Flood Basalt in Oregon, preserves interflow paleosols that record the climatic warming. Because they formed in situ, the chemical composition of the protolith is well-constrained. As a result, it is possible to model weathering of the basalt and soil formation under a variety of atmospheric pCO_2 conditions and to compare those results with quantitative studies of the actual paleosols. Comparison of modelling runs with atmospheric pCO_2 ranging from 0.1-20 PAL (present atmospheric levels) to paleosol data suggests that near-modern pCO_2 levels are unlikely for the middle Miocene climatic optimum. Even when accounting for elevated soil pCO_2 due to the reconstructed plant cover, atmospheric levels of 2-7 PAL are necessary. This suggests that warming during the middle Miocene climatic optimum was due to elevated atmospheric pCO_2 and that climate change and CO_2 levels were coupled for this interval.

GC61A-06 1015h INVITED

Glacial / Interglacial pCO_2 Cycles: Still Searching

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The cause of the glacial / interglacial pCO₂ cycles remains elusive. What are we missing?

Direct effect of Fe fertilization. Pro: Iron deposition to Antarctica precedes termination pCO₂ rise. Con: Might work in a box model but not in current GCMs. The difference, according to Toggweiler, is the extent of equilibration of high latitude surface waters. The processes that maintain disequilibrium in the GCMs operate even more strongly in the real ocean, so my unproven hunch is that the Fe fertilization would be insufficient in the real world, too. If not, the GCMs upon which CO₂ uptake calculations are based would be seriously in error.

Nutrient inventory of the ocean, driven by exposure of the continental shelves. Pro: pCO₂ broadly follows ice volume (with exception of terminations, where it leads). Con: If CaCO₃ production is stimulated along with organic carbon, then the CaCO₃ compensation response kills the pCO₂ drawdown.

Weathering vs. CaCO₃ deposition on continental shelves. Pro: We know that the flooding and exposure of the continental shelves must have perturbed the ocean CaCO₃ cycle profoundly. Con: The expected effects of this perturbation are not seen in deep sea CaCO₃ distribution.

Rain ratio shift, driven by increase in ocean Si. Pro: Ge/Si suggests LGM increase in Si weathering; increased dust deposition might be another source. Con: The ballast model for organic carbon sinking in ocean interior says that CaCO₃ carries 80% of the organic matter to the sea floor, making it difficult to change the OrgC/CaCO₃ ratio.

Southern Ocean physical processes or deep ocean temperature. Pro: Deep ocean temperature correlates with pCO₂. Con: Results from Stage 3, and from models, suggests that the termination pCO₂ rise is larger than can be accounted for by deep ocean temperature change alone.

GC61A-07 1035h

Limited Role of Export Production in Glacial-Interglacial CO₂ Cycles?

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Recent *in situ* experiments in the ocean have shown that marine productivity increases when iron availability increases. It has long been hypothesized that this effect may be responsible for part of the 80 ppm drawdown in atmospheric CO₂ at the Last Glacial Maximum (LGM), when atmospheric dust deposition was >2 times larger than it is today. Results from models of varying complexity suggest that this effect is responsible for 8-40 ppm, and for large regional changes in biological export production in the ocean. Here we use observations and a model to assess whether or not the remaining CO₂ drawdown not related to dust increase is also associated to changes in export production. We study two time periods: the LGM where all physical, chemical and biological changes were at their maximum intensity, and Stage 5a-d (80 to 110 kyr ago) where atmospheric dust deposition had not yet started to increase but CO₂ had already gone down by 50 ppm.

We compiled a global dataset of export production using 10 different indicators from over 130 deep-sea cores for the LGM, and from over 30 cores for Stage 5a-d. To investigate the mechanisms, we used a state-of-the-art ocean biogeochemistry model forced by LGM boundary conditions, with and without enhanced atmospheric dust deposition.

The observations highlight distinct regional changes in export production. At the LGM compared to today: export production was reduced south of 50°S and in the eastern North Pacific, but increased in Subantarctic and northwest Pacific. During Stage 5a-d, export production south of 50°S was already reduced to near-glacial levels, but it had not yet increased in the Subantarctic. The model can reproduce the patterns of export production during Stage 5a-d with changes in ocean circulation only. However, to reproduce the LGM patterns, increased iron deposition must be further imposed. The model suggests that increased export production only had an impact on atmospheric CO₂ between Stage 5a-d and the LGM.

We have focused so far on the South Atlantic ocean. Based on observations in that region, our analysis suggests that the first 50 ppm of atmospheric CO₂ drawdown would not be caused by an increase in export production, but would be more consistent with changes in physical or chemical processes.

URL: http://www.bgc-jena.mpg.de/bgc.prentice/projects/green_ocean/index.html

GC61A-08 1050h INVITED

Postglacial Terrestrial Carbon Dynamics and Atmospheric CO₂

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Combining PMIP climate model results from the last glacial maximum (LGM) with biome modelling indicates the involvement of both cold, dry climate and physiological effects of low atmospheric CO₂ in reducing tree cover on the continents. Further results with the LPJ dynamic vegetation model agree with independent evidence for greatly reduced terrestrial carbon storage at LGM, and suggest that terrestrial carbon storage continued to increase during the Holocene. These results point to predominantly oceanic explanations for preindustrial changes in atmospheric CO₂, although land changes after the LGM may have contributed indirectly by reducing the aeolian marine Fe source and (on a longer time scale) by triggering CaCO₃ compensation in the ocean.

GC61A-09 1110h

What can Re-growth of the Terrestrial Biosphere and the "Coral Reef Hypothesis" Tell us About the Primary Controls on Atmospheric CO₂ at Glacial Termination?

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Despite the identification of numerous different biogeochemical mechanisms for controlling atmospheric CO₂, we still do not fully understand why CO₂ was some 90 ppm lower during glacial than interglacials. Here, we analyze CO₂ changes since the time of the last glacial maximum in a time-dependent manner with the aid of an atmosphere-ocean-sediment carbon cycle model, focusing on the role of two key changes in the global carbon cycle we know to have taken place the re-growth of the terrestrial biosphere and increased shallow water carbonate deposition. We find that contrary to recent speculations, the land biota does not appear to make a significant contribution to the 20 ppm increase in atmospheric CO₂ observed during the late Holocene. Instead, we demonstrate that the late Holocene rise is consistent with the known history of increased deposition of shallow-water carbonates a revision of the "coral reef hypothesis". By subtracting the combined influence on atmospheric CO₂ of these two key processes from recent high-resolution ice core records, we show that the CO₂ change remaining to be accounted for is mainly restricted to two periods of rapid rise, occurring synchronous with Southern Hemisphere warming. This allows us to place strong constraints on the nature of the remaining processes, and propose that these must involve changes in: sea surface temperatures, "iron fertilization" of the biota, and ocean circulation and sea ice extent.

GC61A-10 1125h INVITED

What Caused the 20 ppm Rise in Atmospheric CO₂ Content Over the Last 8000 Years?

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The CO₂ record in the Taylor Dome Antarctica ice core clearly demonstrates that during the last 8000

years, the CO₂ content of the atmosphere rose from 260 to 280 ppm. Based on shaly ¹³C results, Indermühle et al conclude that this rise reflects a 195-gigaton C (i.e., huge) decrease in terrestrial biomass. My feeling is instead that it reflects an early post glacial increase in terrestrial biomass. In this talk, I summarize an attempt to determine whether, as required by either scenario, the CO₂ rise was accompanied by an 8 μmol/kg decrease in deep carbonate ion concentration.

GC61A-11 1145h

How Strong is the Organic Pump in the Ocean?

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An average parcel of oceanic deep water contains about 15% more DIC than warm, low-latitude surface waters. A method for separating the deep DIC excess into its solubility, soft tissue, and carbonate components has been described by Volk and Hoffert (1985). The carbonate component is determined by using the alkalinity difference between deep water and average surface water. The soft tissue difference is determined by using the phosphate difference from average surface water. The carbonate and organic components are subtracted from the overall DIC difference to determine the strength of the solubility component. According to Volk and Hoffert, the organic or soft tissue pump accounts for more than half of the surface-to-deep DIC difference in the ocean. The carbonate and solubility pumps come in a distant second and third, respectively, in relation to the organic pump.

The three components are separated here using an ocean model. The strength of the solubility pump is determined by running the model to a steady state with its biological processes switched off. The strength of the organic pump is determined with the models solubility and carbonate components switched off. The only agreement found between the model-based technique and that of Volk and Hoffert (1985) is in regard to the strength of the carbonate pump: the alkalinity difference between surface water and deep water turns out to be a fairly good predictor for the surface-to-deep DIC difference in the carbonate-only model. The surface-to-deep phosphate difference, on the other hand, is a poor predictor for the surface-to-deep DIC difference in the organic-only model. The organic pump in the model accounts for only 35% of the overall surface-to-deep DIC difference in the full model and, as such, only slightly exceeds the carbonate contribution at 25%. This is somewhat surprising, as the organisms in the model produce four times more organic C than CaCO₃. The organic pump in the ocean is relatively weak because of the way that new deep water is formed in the Southern Ocean and because of the way that this process allows the CO₂ from organic particles to cycle back up to the upper ocean via the atmosphere.

GC62A MCC: 102 Saturday 1330h

Carbon Cycle and Climate: Past, Present, and Future II (joint with A, B, H, OS, PP)

Presiding: N Zeng, University of

Maryland; M Heiman,

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GC62A-01 1330h

Variability of terrestrial CO₂ fluxes after volcanic eruptions

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Recent analyses report that terrestrial biospheric processes play a large role in the interannual variability in atmospheric CO₂ concentrations, ¹³C/¹²C ratios and O₂ concentrations. We use a biogeochemical