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PERSPECTIVES

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PALEOCLIMATE:
Enhanced: CO_2 and Climate Change

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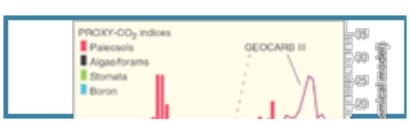
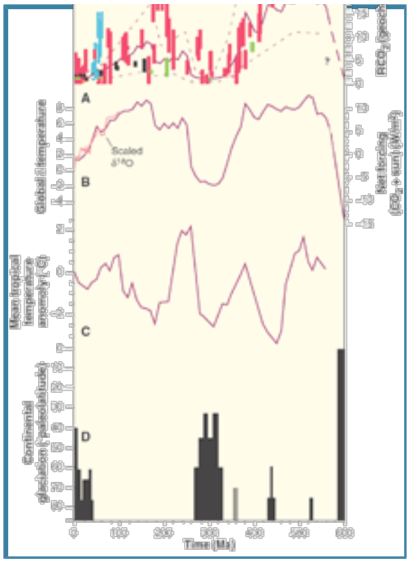
Geologists have long known that on time scales of tens of millions of years, intervals of continental glaciation were interspersed with times of little or no ice [HN1]. The magnitude of warmth during these warm intervals is impressive. At times during the Cretaceous [about 65 to 145 million years ago (Ma)], duck-billed dinosaurs roamed the northern slope of Alaska. Deep and bottom waters of the ocean, now near freezing, could reach a balmy 15°C.

In the 1980s, a convergence of results from paleoclimate data and geochemical and climate models suggested that such long-term variations in climate were strongly influenced by natural variations in the carbon dioxide (CO_2) content of the atmosphere [HN2] (1). Lately, some geochemical results have raised concerns about the validity of this conclusion. CO_2 concentrations over the past 65 million years appear to have reached low levels well before the most recent phase (the past 3 million years) of Northern Hemisphere glaciation. This is especially true for times of elevated temperatures at about 50 to 60 Ma and 16 Ma, when CO_2 was apparently low (2-4). A study spanning the Phanerozoic [HN3] (the past 540 million years) also suggests some decoupling between times of predicted high CO_2 and some climate indices (5).

In light of these results, it is important to reevaluate the validity of the assumed CO_2-climate link. Here we address this issue by comparing estimates of Phanerozoic CO_2 variations (6) and net radiative forcing [HN4] with the continental glaciation record (7, 8) and low-latitude temperature estimates (5) (see the figure).





Records of change. (**A**) Comparison of CO_2 concentrations from the GEOCARB III model (6) with a compilation (9) of proxy-CO_2 evidence (vertical bars). Dashed lines: estimates of uncertainty in the geochemical model values (6). Solid line: conjectured extension to the late Neoproterozoic (about 590 to 600 Ma). RCO_2, ratio of CO_2 levels with respect to the present (300 parts per million). Other carbon cycle models (21, 22) for the past 150 million years are in general agreement with the results from this model. (**B**) Radiative forcing for CO_2 calculated from (23) and corrected for changing luminosity (24) after adjusting for an assumed 30% planetary albedo. Deep-sea oxygen isotope data over the past 100 Ma (13, 14) have been scaled to global temperature variations according to (7). (**C**) Oxygen isotope-based low-latitude paleotemperatures from (5). (**D**) Glaciological data for continental-scale ice sheets modified from (7, 8) and based on many sources. The duration of the late Neoproterozoic glaciation is a subject of considerable debate.

Estimates of CO_2 variations are based on carbon cycle modeling [HN5] and on geochemical proxies [HN6]. Modeled oscillations in CO_2 (see panel A in the figure) result from an interplay of outgassing and weathering changes due to, for example, uplift of mountains. The large downward trend in CO_2 reflects the appearance of vascular land plants about 380 to 350 Ma, which accelerated silicate weathering [HN7] and created a new sink of more bacterially resistant organic matter (lignin) in marine and nonmarine sediments. CO_2 proxy estimates (panel A) (9) are based on indices whose variations correlate with atmospheric CO_2--paleosols (fossilized soils), marine sedimentary carbon, the stomata of fossil leaves, and the boron isotopic composition of carbonate fossils. There is good first-order agreement between modeling and proxy estimates of CO_2 oscillations (panel A), especially given the considerable uncertainties in both the model and the proxies. Notable disagreements can be seen from 270 to 290 Ma (11) and 150 to 180 Ma (12) on the basis of paleosol analyses and from 55 to 65 Ma on the basis of boron isotope results.

For comparison with climate indices, it is important to consider the net radiative forcing, which combines the logarithmic relation between CO_2 concentration and radiative forcing with estimated increases in the sun's output [HN8] over time (panel B). The latter term, generally considered robust (10), corresponds to a ~1% increase in the solar constant per hundred million years and modifies the relative size of the early Phanerozoic and Mesozoic (245 to 65 Ma) CO_2 peaks substantially.

As discussed by Veizer *et al.* (5) [HN9], there is a major discrepancy during the mid-Mesozoic (120 to 220 Ma) between cold low-latitude temperatures deduced from the oxygen isotopic composition ($\delta^{18}O$) [HN10] of fossils (panel C) and high levels of CO_2 and net radiative forcing (panel B). The low-latitude $\delta^{18}O$ data are at variance with other climate data that show high-latitude warming and an absence of large-scale continental glaciation (panel D). The overall low correspondence between low-latitude $\delta^{18}O$ and net radiative forcing begs for an explanation, however, especially because of the striking correspondence between low net radiative forcing (panel B) and major continental glaciation from 256 to 338 Ma (panel D). Comparison of the records of glaciation and CO_2 forcing indicates that CO_2 can explain 37% of the variance on a time scale of 10 million years. The combined net radiative forcing from CO_2 and the sun explains 50% of the variance. In addition, net radiative forcing changes over the past 100 million years track estimated changes in global temperature (panel B) derived from the deep-sea oxygen isotope record (13, 14).

How can the discrepancies between models and some data, and between different data, be reconciled? In the case of the relatively short-lived Late Ordovician glaciation [HN11] (about 440 Ma), which occurred at a time of high net radiative forcing, climate models suggest that the unusual continental configuration of Gondwanaland [HN12] (essentially a large landmass tangent to the South Pole) could result in conditions where high CO_2 and glaciation can co-exist (15). A brief negative excursion of CO_2 at this time may have also contributed to this glaciation (16). Changes in ocean circulation, due [HN13], for example (17), to the opening and closing of "ocean gateways" (Panama straits, Drake Passage), could have altered ocean heat transport, further affecting ice sheet growth and perhaps even CO_2 in a manner not addressed by the model. Other brief intervals of glaciation between 544 and 245 Ma (see the figure) are beyond the time resolution of the model.

But the persistent Phanerozoic decorrelation between tropical $\delta^{18}O$ and net radiative forcing demands a more comprehensive explanation. One possibility is that Veizer *et al.*'s analysis (5) does not isolate ocean temperature variations. Substantial bias may result from diagenesis of samples or unaccounted-for changes in the $\delta^{18}O$ of seawater that undermine the assumption of random errors, one of the foundations of the study.

However, if further scrutiny confirms the Veizer *et al.* results, we must turn to the complexities of climate modeling to seek an explanation. For example, modelers have long known (18) that climate change in the tropics can be largely decoupled from mid-high-latitude ice volume changes because of the limited length scale (~1500 to 2000 km) over which a local perturbation such as an ice sheet can affect temperatures. The tropics may thus respond to other factors, such as changes in tectonic boundary conditions.

Furthermore, the response of the atmosphere-ocean circulation during times of low continental ice volume is particularly difficult to model. During the warm period at 55 Ma, high-latitude temperatures increased substantially (>10°C), but tropical temperatures may have been almost constant or even slightly lower than today (19). [This interpretation has been challenged, however, on the grounds of possible diagenetic alteration of the oxygen isotope temperature signal (20).] A similar explanation could apply to the mid-Mesozoic discrepancies discussed by Veizer *et al.* Such altered zonal gradients are often attributed to increased ocean heat transport, but to our knowledge, no coupled climate model simulations have ever produced the observed patterns.

The first-order agreement between the CO_2 record and continental glaciation continues to support the conclusion that CO_2 has played an important role in long-term climate change. The Veizer *et al.* data, if correct, could be considered a Phanerozoic extension of a possible dilemma long known for the early and mid-Cenozoic.

To weigh the merits of the CO_2 paradigm, it may be necessary to expand the scope of climate modeling. For factors responsible for the presence or absence of continental ice, the CO_2 model works very well. In contrast, there are substantial gaps in our understanding of how climate models distribute heat on the planet in response to CO_2 changes on tectonic time scales. Given the need for better confidence in some of the paleoclimate data and unanticipated complications arising from altered tectonic boundary conditions, it may be hazardous to infer that existing discrepancies between models and data cloud interpretations of future anthropogenic greenhouse gas projections.

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HyperNotes

Related Resources on the World Wide Web

GENERAL HYPERNOTES

The Carbon Dioxide Information Analysis Center provides a glossary and a selection of climate change links.

S. Baum, Department of Oceanography, Texas A&M University, makes available a Glossary of Oceanography and the Related Geosciences with References.

The Global Change Web site, presented by the Pacific Institute for Studies in Development, Environment, and Security, provides a glossary and links to Internet resources.

The World Wide Web Virtual Library: Paleoclimatology and Paleoceanography is maintained by P. Farrar, Naval Oceanographic Office, Stennis Space Center.

The Earth Science Resources Web page of R. H. Cummins, School of Interdisciplinary Studies, Miami University, OH, provides links to Internet resources related to paleoclimate, greenhouse warming, El Niño, and climate change.

The U.S. Global Change Research Program (USGCRP) provides a section on paleoenvironment and paleoclimate; a collection of Internet links is included. The U.S. Global Change Research Information Office (GCRIO) provides access to data and information on global environmental change research, adaptation/mitigation strategies and technologies, and global change related educational resources on behalf of USGCRP. NOAA's National Climatic Data Center provides links to climate Internet resources.

NASA's Global Change Master Directory is a comprehensive searchable directory of descriptions of data sets relevant to global change research; included are links to data on paleoclimate.

The NOAA Paleoclimatology Program at the National Geophysical Data Center is a central resource for paleoclimate data, research, and education. An introduction to paleoclimatology science is provided.

The GRID (Global and Regional Integrated Data) Centre, an office of the United Nations Environment Programme (UNEP) in Arendal, Norway, offers an illustrated introduction to climate change.

The Encyclopedia of the Atmospheric Environment from the Atmosphere, Climate and Environment Information Programme, Manchester Metropolitan University, UK, offers introductory articles on climate and climate change topics. An introduction to paleoclimate change is included.

Britannica.com offers *Encyclopædia Britannica* articles on climate and climatology. The article on climate has a section on climatic variations and change.

C. Scotese's PALEOMAP Project provides illustrated introductions to Earth history and climate history; a paleoclimate animation is also provided.

Planet Earth and the New Geosciences is a hypermedia textbook by V. Schmidt and W. Harbert, Department of Geology and Planetary Science, University of Pittsburgh. Chapters on the atmosphere and climate and climates of Earth are included.

Fundamentals of Physical Geography, a Web textbook by M. Pidwirny, Department of Geography, Okanagan University, Kelowna, BC, Canada, has a section on meteorology and climatology that includes presentations on Earth's climatic history and causes of climate change. A glossary is provided.

The Department of Earth and Environmental Sciences, Columbia University, makes available lecture notes for a course on the climate system.

R. Myneni, Department of Geography, Boston University, provides lecture notes and Web resources for a course on global climate change and environmental impacts.

E. Takle, Department of Geological and Atmospheric Science, Iowa State University, provides lecture notes for a Web course on global change.

The University of Michigan Global Change Program offers lecture notes on the physical processes of global change. Included are lecture notes on climate patterns and paleoclimates and lecture notes on the paleoclimate record and climate modeling.

S. Fitzsimons, Department of Geography, University of Otago, NZ, provides lecture notes for a course on climate change of the past.

The School of the Environment, University of Leeds, UK, makes available lecture notes for a course on the scientific issues of climate change.

J. Adams, Department of Geographical and Environmental Studies, University of Adelaide, Australia, provides lecture notes for a course on environmental change.

D. Burdige, Department of Ocean, Earth, and Atmospheric Sciences, Old Dominion University, Norfolk, VA, provides lecture notes in Adobe Acrobat format for a course on global environmental change. Lecture notes on global carbon cycles (parts one and two) and glacial cycles (parts one and two) are included.

Carbon Dioxide and Climate Change is a 1997 colloquium proceedings made available on the Web by the National Academy Press.

Global Environmental Change: Research Pathways for the Next Decade is a 1999 National Research Council report that includes a paleoclimate overview and a chapter on modeling.

An article by T. Crowley titled "Remembrance of things past: Greenhouse lessons from the geologic record" appeared in the Winter 1996 issue of *Consequences*, available from GCRIO.

The 1997 annual report of the Geological Survey of Norway included a chapter by

E. Larsen titled "The climate of the past -- A key to understanding future climate development."

The 28 September 1999 issue of *Eos* had an article by T. Ledley *et al*. titled "Climate change and greenhouse gases."

The 2000 October 13 issue of *Science* had a review article by P. Falkowski *et al*. titled "The global carbon cycle: A test of our knowledge of Earth as a system."

The 27 April 2001 issue of *Science* was a special issue on paleoclimate. The issue had a review by J. Zachos *et al*. titled "Trends, rhythms, and aberrations in global climate 65 Ma to present."

NUMBERED HYPERNOTES

1. **Cracking the Ice Age**, a Public Broadcasting Service **NOVA Online** Web site, includes a **presentation about climate variation** by K. Maasch titled "The big chill." **J. Aber**, Earth Science Department, Emporia State University, KS, provides an **introduction to ice ages** in the **lecture notes** for a course on **Ice Age environments**. **J. Adams** provides **lecture notes** on ice sheets and glaciers for a course on **environmental change**. **R. T. Patterson**, Department of Earth Sciences, Carleton University, Ottawa, provides a presentations on the **ice ages** and the **hot house/ice house world** for a **course on climate change**. **Glacier**, a presentation of the **Department of Geology and Geophysics**, Rice University , includes a section about the **causes of ice ages**. **W. Locke**, Department of Earth Sciences, Montana State University, Bozeman, makes available presentations on **glaciers with time: climate** and **glaciers and climate: space** in a **hypertext introduction** to glaciers and glacial geology. **E. Thomas**, Department of Earth and Environmental Sciences, Wesleyan University, offers lecture notes on ice ages (parts **one** and **two**) in a collection of **notes on paleoceanogphy**. **G. Lash**, Department of Geosciences, Fredonia State University, NY, provides lecture notes on **climatic changes in the past** and **mechanisms of climate change** for a **course** on catastrophic weather and climatic change. The **USGS Eastern Region Climate History/Hazards Team** offers a **presentation** titled "Warm Climates: Variability - Extremes - Impacts." ***Nature*** had a 11 January 2001 **Feature of the Week** on ice ages and instabilities. **Science@NASA** presents a 20 October 2000 **feature article** titled "Earth's fidgeting climate."

2. **B. Shakhashiri**, Department of Chemistry, University of Wisconsin, provides an introduction to **carbon dioxide**. The **Athena** Web site, a part of NASA's **Learning Technologies Project**, offers information on **carbon dioxide** and other atmospheric greenhouse gases in a presentation on **global change**. **E. Takle** provides lecture notes on **carbon dioxide** for a **course on global change**. **J. Varekamp**, Department of Earth and Environmental Sciences, Wesleyan University, offers lecture notes and Internet links for a course on **carbon dioxide**; **lecture notes** on CO_2, weathering, and climate are included. The **Atmospheric Chemistry Division** (ACD) of the National Center for Atmospheric Research makes available a **chapter** on atmospheric chemistry and climate from ***Atmospheric Chemistry and Global Change***, a textbook by ACD staff. The **NASA Goddard Institute for Space Studies** makes available an **article** by Q. Ma titled "Greenhouse gases: Refining the role of carbon dioxide." The 15 September 2000 issue of *Science* had a **News Focus article** by R. Kerr titled "Ice, mud point to CO_2 role in glacial cycle" about a **report** in that issue by N. Shackleton titled "The 100,000-year ice age cycle identified and found to lag temperature, carbon dioxide, and orbital eccentricity."

3. The **Department of Geology and Geophysics**, University of Alaska, Fairbanks, presents a **geologic time scale**. A guide to **geologic time divisions** is provided by the **University of California Museum of Paleontology**. The **Visualizing Earth** Web site provides an introduction to the **Phanerozoic geologic time scale**.

4. The **UNEP GRID Centre** in Norway provides an introduction to **radiative forcing**. The University of Leeds **course on the scientific issues of climate change** includes **lecture notes** on radiative balance of the atmosphere and the greenhouse effect and **lecture notes** on radiative forcing, global warming potentials, and climate feedbacks. **R. Myneni** provides **lecture notes** on radiative forcing of climate change for a **course** on global climate change and environmental impacts.

5. The **Hadley Centre for Climate Prediction and Research**, a part of the UK Met Office, provides an introduction to the **carbon cycle**, as well as information about **climate modeling** and a **presentation** on ocean carbon cycle modeling. M. Pidwirny's **Fundamentals of Physical Geography** includes a section on the **carbon cycle**. The University of Michigan **global change course** offers a presentation on the **global carbon cycle**. **V. McKenna**, Department of Geological Sciences, University of Michigan, offers lecture notes on the **carbon cycle** for a course on **oceanography**. **R. Arvidson**, Earth and Planetary Remote Sensing Laboratory, Washington University, St. Louis, offers lecture notes on the **carbon cycle** for a **course** on land dynamics and the environment. ***Introduction to Atmospheric Chemistry*** by **D. Jacob**, Atmospheric Chemistry Modeling Group, Harvard University, includes a section on the **carbon cycle**. The 10 July 1998 issue of *Science* had a **Perspective** by P. Tans and J. White about the global carbon cycle titled "In balance, with a little help from the plants." **E. Kasischke**, Department of Geography, University of Maryland, offers lecture slides on **carbon cycle modeling** for a **course** on biogeography. The March 1998 issue of ***Science & Technology Review***, published by the Lawrence Livermore National Laboratory, had an **article** by G. Wilt about carbon cycle modeling titled "Tracing the role of carbon dioxide in global warming."

6. **W. White**, Department of Geological Sciences, Cornell University, provides lecture notes (in Adobe Acrobat format) on the carbon cycle, isotopes, and climate (parts **one** and **two**) for a course on **isotope geochemistry**. The **NOAA Paleoclimatology Program** provides an introduction to **proxy climatic data**. **E. Takle** offers **lecture notes** titled "Paleoclimate: Using proxy data to reconstruct past climates" for a course on **global change**. The **1996 report** *Natural Climate Variability on Decade-to-Century Time Scales*, available from the **National Academy Press**, has a chapter on **proxy indicators of climate**.

7. **P. Olsen**, Department of Earth and Environmental Sciences, Columbia University, offers **lecture notes** titled "Innovations and biogeochemical revolutions: The geological carbon cycle" and **lecture notes** on the Paleozoic and the rise of plants for a **course** on the life system. **R. Gastaldo**, Department of Geology, Colby College, Waterville, ME, offers **lecture notes** on early evidence for land inhabitation for a **paleobotany course**. The **History of Palaeozoic Forests** Web pages provided by H. Kerp, **Palaeobotanical Research Group**, University of M ¸nster, Germany, include a section on **early land plants**. The 1997 April 25 issue of *Science* had a **Perspective** by R. Berner titled "The rise of plants and their effect on weathering and atmospheric CO_2" and a **report** by G. Retallack titled "Early forest soils and their role in Devonian global change." **W. Cheng** Department of Environmental Studies, University of California, Santa Cruz, presents lecture notes on

rock weathering for a course on the physical and chemical environment. M. Pidwirny's Fundamentals of Physical Geography section on weathering.

8. Resources in Atmospheric Sciences, made available by B. Geerts, Department of Atmospheric Sciences, University of Wyoming, includes an introduction to changes in the solar constant. The University of Leeds course on the scientific issues of climate change includes lecture notes on solar effects on climate. The Winter 1996 issue of *Consequences* had an article by J. Lean and D. Rind titled "The Sun and climate." *Solar Influences on Global Change* is a 1994 National Research Council report available from the National Academy Press.

9. The 7 December 2000 issue of *Nature* had an article (abstract from the *Nature* Asia Web site) by J. Veizer, Y. Godderis, and L. François titled "Evidence for decoupling of atmospheric CO_2 and global climate during the Phanerozoic eon" (5) as well as a News and Views article by L. Kump titled "What drives climate." *Nature* also provides a 7 December 2000 Science Update by H. Langenberg about this research titled "Force of change not necessarily CO_2." J. Veizer is in the Department of Earth Sciences, University of Ottawa and at the Institut für Geologie, Mineralogie und Geophysik (faculty page for Veizer), Ruhr Universität, Bochum, Germany. Y. Godderis and L. François are at the Laboratory for Planetary and Atmospheric Physics, Institut d'Astrophysique et de Géophysique, Université de Liège, Belgium. The University of Ottawa issued a news release about this research. Space Daily offers a 6 December 2000 article about Veizer's research titled "Climate modeling must consider all 'greenhouse' gases." The Australian Broadcasting Corporation offers a 8 December 2000 article about this research titled "CO_2 emissions off the hook?"

10. An entry about oxygen isotope analysis is included in S. Baum's glossary. The NASA Goddard Institute for Space Studies makes available an article by G. Schmidt titled "Cold climates, warm climates: How can we tell past temperatures?" about oxygen isotope analysis of fossils. J. Aber provides an introduction to oxygen-isotope ratios in his lecture notes on paleoclimate reconstruction. E. Thomas provides lecture notes titled "Oxygen isotopes: The thermometer of the Earth" in a collection of notes on paleoceanography. S. Fitzsimons provides lecture notes on marine records of climate change with a section on oxygen isotope analysis for a course on climate change of the past. A section on the use of stable oxygen isotopes in ocean-climate research is included in the chapter on paleoceanography in the online marine geology textbook provided by H. Schrader, Geologisk Institutt, University of Bergen, Norway. W. White offers lecture notes (in Adobe Acrobat format) on oxygen isotope paleoclimatology (parts one and two) for a course on isotope geochemistry.

11. Ordovician is defined in S. Baum's glossary. The University of California Museum of Paleontology provides an introduction to the Ordovician and information on Ordovician tectonics and paleoclimate. The Hooper Virtual Paleontological Museum offers a presentation on the Ordovician mass extinctions and speculations about the causes.

12. S. Baum's glossary defines Gondwanaland. *Encyclopædia Britannica* provides an introduction to Gondwanaland. The historical perspective chapter of *This Dynamic Earth: the Story of Plate Tectonics*, a USGS Web publication, provides information on Gondwanaland. The Dynamic Earth Web site, provided by the Department of Earth Sciences, Monash University , Melbourne,

Australia, makes available an animated presentation on **Gondwanaland**. The **plate tectonics presentation** from the **University of California Museum of Paleontology** includes animations of **continental drift**.

13. The **UNEP Division of Environmental Conventions** provides a **climate change fact sheet** on **how the oceans influence climate**. NASA's **Earth Observatory** Web site includes a presentation by D. Herring on **oceans and climate**, as well as other features on **oceanic** and **atmospheric** topics. **J. Adams** offers lecture notes on **oceans and climate change** for a **course** on environmental change. **M. Tomczak**, School of Chemistry, Physics and Earth Sciences, Flinders University of South Australia, provides lecture notes on the **ocean and climate** for a **physical oceanography course**. J. Morelock, **Geological Oceanography Program**, Department of Marine Sciences, University of Puerto Rico, Mayagüez, offers lecture notes on **paleoceanography** for a course on **marine geology**. **S. Rahmstorf**, Potsdam Institute for Climate Impact Research, Germany, offers a **presentation** titled "Ocean currents and climate change." **S. Lund**, Department of Earth Sciences, University of Southern California, provides **lecture notes** for an **oceanography course**; a presentation on **paleoclimate and paleoceanography** is included.

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