um is unlikely to proceed entirely through gas-phase ion-molecule reactions because positively charged carbon species (carbonium ions) cease to react with H_2 before they are fully saturated. Observation of saturated hydrocarbons in dense clouds, either frozen on grains or as gases, would thus provide strong evidence that reactions on grains play major roles in interstellar chemistry.

Comets bear some similarity to interstellar ices in dark clouds, and insights gained into their chemistry can therefore provide some clues for the chemistry taking place in dark clouds. Most of the time, comets orbit far from the sun, allowing them to remain virtually unchanged since the origin of the solar system (*11*). The high-resolution infrared telescope on Mauna Kea, Hawaii, detected the hydrocarbons C_2H_2, C_2H_6, and CH_4, along with CO and H_2O in comet Hyakutake. Comet Hale-Bopp was observed at wavelengths from 2.4 to 195 μm with the ISO when the comet was about 2.9 astronomical units from the sun (*12*). The gas-phase abundances of C_2H_2 and C_2H_6 were found to be about the same, at about 0.5% of the abundance of H_2O (*12*).

C_2H_4 was not detected by infrared spectroscopy in these comets despite the relatively strong intensities of the related molecules C_2H_2 and C_2H_6. The abundance of C_2H_4 is generally observed to be low in the solar system; for example, C_2H_4 is missing in Saturn and its moon Titan, where other hydrocarbons with two carbon atoms are common. To find out why, we must consider the channels through which these molecules form.

There are several gas-phase channels for the formation of C_2H_2 (such as $C^+ + CH_4 \rightarrow C_2H_3^+ + H$ and $C_2H_3^+ + e^- \rightarrow C_2H_2 + H$). The presence of C_2H_2 in comets is therefore reasonable. C_2H_6 may form by consecutive hydrogenation of C_2H_2 trapped in cometary ice, $C_2H_2 \rightarrow C_2H_3 \rightarrow C_2H_4 \rightarrow C_2H_5 \rightarrow C_2H_6$, with C_2H_4 as an intermediate. We have found that when solid C_2H_2 was reacted with H atoms at 10 K, C_2H_6 was the only product; no C_2H_4 could be detected (*8*). This finding is in accord with the observation of comets Hyakutake and Hale-Bopp. C_2H_4 is absent because the addition reaction $H + C_2H_2 \rightarrow C_2H_3$ is the rate-controlling process and the subsequent reactions to form the final product C_2H_6 proceed much faster than the initial one. A model of gas-grain chemistry in dense clouds correctly predicted that the grain surface concentrations of C_2H_2 and C_2H_6 are much greater than that of C_2H_4 (*13*).

Usually, chemical reaction rates decrease with decreasing temperature. We found, however, that in the reaction of hydrogen atoms with solid C_2H_2, C_2H_4, C_2H_6, CO, and SiH_4, the product yields increased drastically with decreasing temperature. The rate of reaction of hydrogen with C_2H_2 to form C_2H_6 increased by about four orders of magnitude when the reaction temperature was decreased from 50 to 10 K.

Such a negative temperature dependence of the rate constants for tunneling reactions has been predicted (*14*). The argument runs as follows: The many-body reactant-substrate and product-substrate interactions produce a dense spectrum of vibrational energy levels. The quasi-continuous set of vibrational levels of the reactant-substrate system acts as a dissipating channel and promotes the forward reaction (*15*). This becomes more favorable at lower temperature because thermal fluctuations are suppressed.

The fact that the temperature in dark clouds is kept at about 10 K is thus crucial for the chemical evolution in dark clouds. If the temperature of the molecular clouds were higher, the rate of chemical evolution would be slower because of the decrease of the rates of the tunneling reactions.

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PERSPECTIVES: PALEOCLIMATE

CO_2 and Climate Change

Thomas J. Crowley and Robert A. Berner

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. 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.

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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 (*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 (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 with the continental glaciation record (*7, 8*) and low-latitude temperature estimates (*5*) (see the figure).

Estimates of CO_2 variations are based on carbon cycle modeling and on geochemical proxies. 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 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 agree-

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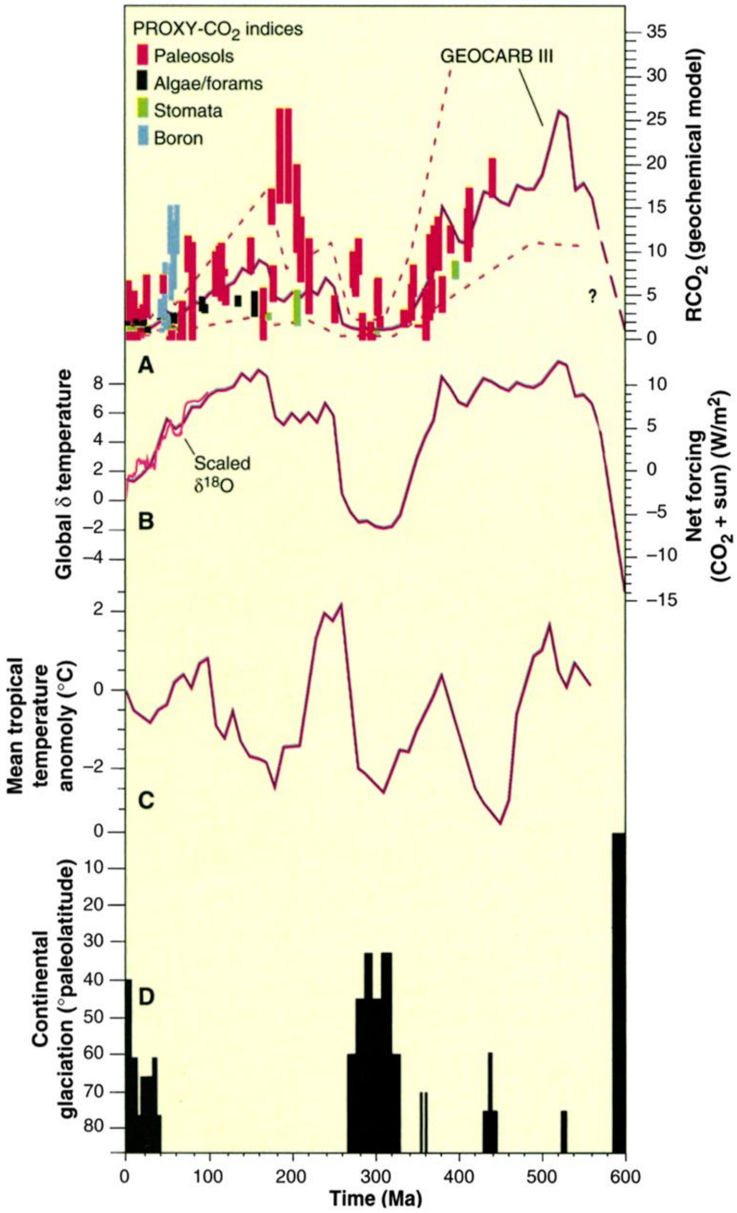
ment between modeling and proxy estimates of CO_2 oscillations (panel A), especially given the considerable uncertainties in both the model and the proxies. Notable disagreements can be seen from 270 to 290 Ma (*11*) and 150 to 180 Ma (*12*) on the basis of paleosol analyses and from 55 to 65 Ma on the 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 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*), there is a major discrepancy during the mid-Mesozoic (120 to 220 Ma) between cold low-latitude temperatures deduced from the oxygen isotopic composition ($\delta^{18}O$) 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 (about 440 Ma), which occurred at a time of high net radiative forcing, climate models suggest that the unusual continental configuration of Gondwanaland (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, 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.



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.

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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PERSPECTIVES: NEUROSCIENCE

Unwrapping Glial Cells from the Synapse: What Lies Inside?

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The central nervous system houses two main kinds of cells—neurons, which move information around the brain in the form of electrical signals, and glia, which until relatively recently have been considered to fulfill only a supportive role. However, an exciting possibility is emerging—the major type of glia, the astrocyte, seems actually to be required for synapse formation and maintenance, and for synaptic efficacy (*1*, *2*).

The long, thin processes of astrocytes ensheathe the synaptic connections between neurons and are therefore well positioned anatomically to contribute to synaptic transmission. Furthermore, these glial cells express a wide variety of neurotransmitter receptors and voltage-gated ion channels, which are important in receiving and integrating neuronal signals (*3*). Two reports in this issue of *Science* by Iino *et al.* on page 926 (*4*) and Oliet *et al.* on page 923 (*5*) use two different animal models and experimental approaches to illuminate astrocytic participation in the workings of the synapse.

Glutamate receptors called AMPA receptors, triggered by the neurotransmitter glutamate, mediate the majority of fast synaptic transmission in the central nervous system (CNS). These receptors are formed by combinations of glutamate receptor subunits, GluR1 through GluR4 (*6*). The GluR2 subunit is of particular functional importance because it confers Ca^{2+} impermeability on the AMPA receptor complex. About a decade ago, soon after the AMPA receptor subunits were cloned, Kettenmann's and Sakmann's laboratories reported that Bergmann glial cells (cerebellar astrocytes) did not express GluR2 and hence their AMPA receptors are Ca^{2+}-permeable (*7*, *8*). Since this discovery, the physiological function of Ca^{2+}-permeable receptors in Bergmann glia has remained a mystery.

The study by Iino *et al.* (*4*) provides the first piece of evidence for a functional role of these receptors. They demonstrate that AMPA receptor–mediated Ca^{2+} influx is important in generating and maintaining the appropriate structural and functional association between the neuronal elements of glutamatergic synapses in the cerebellum and Bergmann glia. They focus on synapses that have been well studied both from a neurocentric as well as a gliocentric perspective.

Parallel fiber and climbing fiber terminals establish synaptic contacts with Purkinje cell dendrites in the cerebellar cortex. Bergmann glia become part of these functional units by extending processes whose thin membrane sheets wrap around these synapses. Glutamate released at these synapses activates both AMPA receptors on Purkinje cells and Bergmann glia, and glutamate transporters on the glia. These thin processes of the Bergmann glia define anatomical and functional three-dimensional compartments termed microdomains near and around the synapse, which define the area of functional interaction of the neurons and glia (*9*). Stimulation of cerebellar synapses between parallel fibers and Purkinje cell neurons leads to an AMPA receptor–mediated increase in the intracellular Ca^{2+} concentration in Bergmann glia.

Iino *et al.* (*4*) modified the molecular composition of AMPA receptors in the Bergmann glia by infecting Purkinje cells with a recombinant adenovirus containing the coding region of the GluR2 gene. As expected, the virally induced introduction of GluR2 into Bergman glia led to the expression of AMPA receptors that display Ca^{2+} impermeability. Conse-

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