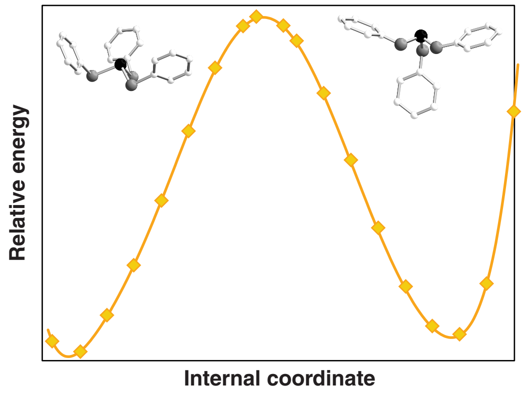

Calculated molecular conformations of triphenyl phosphite (TPP) (*9*). The structure on the right, found in the known crystalline phase of TPP, forms intermolecular hydrogen bonds. The structure on the left, thought to be the standard conformation in the liquid and gas phases, is predicted to only form intermolecular van der Waals interactions. Whether these structures play a role in the liquid-liquid phase transition of TPP remains unknown.

A remaining question in TPP concerns the nature of this short-range structure. Is it primarily associated with a different conformation of the TPP molecule (see the second figure), or does a much larger structural entity comprising several molecules play a role? Interestingly, the reported critical phenomenon in TPP does not strongly affect any measured thermodynamic properties of the liquid.

In phosphorus, the association of P_4 molecules into clusters or larger covalently bonded units could be the relevant order parameter for the polyamorphic transition. However, a critical point between liquid I and liquid II has not yet been found, nor has the critical nature of the transition been established. Extrapolation of the equilibrium phase line suggests that the critical point in phosphorus may occur at negative pressures (see the first figure).

A further, as yet experimentally unexplored question is whether a polyamorphic transition could exhibit a second critical point (referred to as the lower consolute point) at the lower end of the phase boundary between the two liquids. The existence of two critical points would lead to a closed loop in the temperature-density phase diagram (*8*). Such a scenario is likely to occur in polyamorphic systems that rely on orientation-dependent interactions such as hydrogen bonds (*8*).

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PHYSICS

Ancient Lessons for Our Future Climate

Daniel P. Schrag and Richard B. Alley

Humans are changing the amount of carbon dioxide in the atmosphere by burning coal, oil, and gas. The current atmospheric CO_2 concentration is higher than it has been for at least the past 430,000 years (*1*), and perhaps for tens of millions of years (*2*). Over the next 100 years, without substantial changes in energy technology or economic development, the atmospheric CO_2 concentration will rise to 800 to 1000 ppm (*3*). This rise represents a spectacular, uncontrolled experiment that humans are performing on Earth. The paleoclimate record may provide the best guess as to what may happen as a result.

One crude measure of how much the climate will warm in response to an increased atmospheric CO_2 concentration is the climate sensitivity, often taken as the globally averaged warming expected from doubling the atmospheric CO_2 concentration. This sensitivity is usually estimated as between 1.5° and 4.5°C on the basis of results from a suite of complex climate models and from efforts to explain temperature changes over the past century [see discussion in (*4*)]. However, many uncertainties exist in that estimation, including large gaps in our understanding of water vapor and cloud feedbacks on climate.

The study of past climates provides information about the magnitude of, and causes for, many preinstrumental climate changes, allowing for comparison with climate models and an independent assessment of climate sensitivity. Periodic ice ages over the past 2 million years were paced by Earth's orbit around the Sun. However, the synchronous and substantial glaciation in both hemispheres requires some additional feedbacks beyond the orbital variations to amplify the climate response and make it uniform in both hemispheres. Changes in the atmospheric CO_2 concentration are likely responsible for both (*5*). The sea surface temperature in the Western Equatorial Pacific was about 3°C colder during the last ice age than it is today (*6*). Given that this warm and stable area of the world ocean was relatively unaffected by changes in high-latitude ice cover and in ocean circulation, the cooling must be explained predominantly by radiative effects associated with changes in atmospheric CO_2 concentration. This observation yields a climate sensitivity that is on the high end of modern estimates, consistent with model simulations of the ice ages (*7*).

Likewise, warm episodes in Earth's history reveal a similar cautionary lesson. During the Eocene, 50 million years ago, palm trees grew in Wyoming (*8*) and deep ocean temperatures were more than 10°C warmer than present (*9*). Because we do not know exactly how high the atmospheric CO_2 concentration was at that time, we cannot use it as a direct measure of climate sensitivity. However, the extreme warmth at high latitudes—especially during the winter in continental interiors—cannot be simulated by climate models purely through elevating greenhouse gas concentrations (*10*). Special cloud feedbacks must be included that are not present in the models used to predict future climate change (*10*, *11*). This observation suggests that feedbacks may be missing from current models and that future climate change may be underestimated in these models, particularly at high latitudes.

This lesson is supported by an event at the very beginning of the Eocene, 55 million years ago. During the Paleocene-Eocene Thermal Maximum, tropical oceans warmed by 4° to 6°C and high-latitude oceans by 8° to 10°C in less than 10,000 years (*9*). The leading hypothesis for this event involves the release of methane, another powerful greenhouse gas, from the sea floor (*12*). However, the duration of the climate event—50,000 to

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200,000 years in total (*9*)—suggests that the warming was probably caused mainly by an increase in the atmospheric concentration of CO_2 rather than methane, due to the short lifetime of methane in the atmosphere. The issue is still debated (*13*), but the extreme temperature change is consistent with a relatively high climate sensitivity if CO_2 is mainly responsible for the climate event. In addition, the large temperature change near the poles is troubling because there was no permanent sea or land ice at this time. The presumed mechanism for polar amplification in future climate change involves changes in ice cover (*14*). The extreme polar warming at the Paleocene-Eocene Thermal Maximum suggests that some additional feedback causes warming at high latitudes in the real climate system that is not incorporated in the current generation of climate models.

A sensitive system. Increases in atmospheric CO_2 cause Earth's atmosphere to warm. But the extent of the warming depends on the response of other parts of the climate system, including clouds and ice sheets. Reconstructions of past climate variability suggest that these factors may make Earth's climate more sensitive to CO_2 changes than most climate models indicate.

A final lesson from past climates is that climate changes are not always slow and steady, but can occur within decades or even years. The documentation of abrupt changes around the world during the last glacial period [e.g., (*15*)] is a spectacular reminder of how quickly climate can change. The mechanisms responsible for such changes during the ice age probably required a greater extent of land glaciers and sea ice than today, and are therefore unlikely to be experienced in the same way in the near future. However, the response of glaciers on Greenland and Antarctica to enhanced polar warming over the next century is sufficiently uncertain (*16*) that the possibility of sudden changes must be considered.

It would be a grave mistake to take these lessons from ancient climates as a reason to disregard the projections from climate models. The models are not perfect, but they represent the best understanding of the climate system from a century of observations and remain an essential tool for exploring future climate scenarios. Yet it is not surprising that there are some gaps in this understanding, because our atmosphere is heading toward a state far beyond the boundaries of all modern observations and calibrations.

Paleoclimate studies help to fill these gaps. The lessons are surprisingly consistent, whether from warm climates or cold, whether from millions or thousands of years ago: The climate system is very sensitive to small perturbations. The release of greenhouse gases through human activities represents a large perturbation, sending our atmosphere to a state unlike any seen for millions of years. It behooves us to remember the past as we anticipate the future.

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PLANT BIOLOGY

Plant Acupuncture: Sticking PINs in the Right Places

Nicholas J. Kaplinsky and M. Kathryn Barton

The plant hormone auxin affects many important aspects of plant growth and development. For example, auxin influences growth of plants relative to gravity (gravitropism) and light (phototropism), placement of leaf primordia, and the establishment of stem cell niches (*1*–*4*). These processes all depend on differences in the local concentrations of auxin. Such differential auxin concentrations are established through the directed (polar) transport of auxin from sites of biosynthesis (leaves) to sites of action in the shoot and root. In turn, polar auxin transport depends on the asymmetric localization in plant cells of proteins called PINFORMED (PIN) auxin transport facilitators (*5*).

The location of PIN proteins, and hence the direction of polar auxin transport, varies depending on the type of tissue. For instance, in central portions of the root, PIN proteins are localized in basal areas of cells and auxin flow is directed downward. In contrast, in emerging leaf and floral primordia, PIN proteins are localized apically and auxin flow is directed upward (*4*–*6*) (see the figure). Because the localization of PIN proteins has such an important influence on polar auxin transport, plant biologists have sought to understand what determines the placement of PIN proteins in plant cells. On page 862 of this issue, Friml *et al.* (*7*) provide evidence that a major determinant of PIN protein localization in the model plant *Arabidopsis* is the serine-threonine kinase PINOID (PID). High levels of PID activity lead to the apical localization of PIN, whereas low levels lead to the basal localization of PIN.

Arabidopsis mutants that carry a defective *PINFORMED1* (*pin1*) gene make barren "pin-like" inflorescences that largely lack floral primordia (see the figure). Polar auxin transport is reduced in such *pin1* mutants, and inhibitors of polar auxin transport induce the development of pin-like inflorescences in wild-type plants (*8*, *9*). Application of auxin to these barren inflorescences rescues their ability to make pri-

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