genase functions is the mechanism of coupling of Mg–ATP hydrolysis to proton and electron transfers. Free access of protons to the low-potential metal site(s) required to bind and activate N_2 is likely to result in uncontrolled H_2 production; yet protonation of N_2 is essential for NH_3 formation. With the MoFe-protein structure[3] we can begin to address this problem, for it defines the possible access routes for N_2, electrons and protons to the FeMo-cofactor.

The similarities, both structural[4] and kinetic[13], between nitrogenase and at least two other ATP/GTP-dependent energy-transducing systems, the oncogene product p21^{ras} and actomyosin, are intriguing. They give studies on nitrogenase structure and function a significance well beyond that of nitrogen fixation. □

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GLOBAL CHANGE

Lessons from past climates

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THE prediction of future climate change is based largely on general circulation models (GCMs) developed within the constraints of modern observations. The short-term nature of these observations, on top of natural uncertainties about the processes involved, give ample reason to question predicted responses to large perturbations, such as a doubling of atmospheric carbon dioxide. But on page 573 of this issue[1], Hoffert and Covey use data from two very different periods of the Earth's history to show that the estimated climate sensitivities are not unreasonable.

The Intergovernmental Panel on Climate Change (IPCC) has concluded that a global warming of between 1.5 and 4.5 °C is likely for a doubling of carbon dioxide. The majority of GCM projections fall within this range. Much of the range in estimates is attributed to uncertainties associated with cloud–climate feedbacks. The primary objective of Hoffert and Covey is to use two case studies from the Earth's history to derive an estimate, independent of GCMs, of the climate's sensitivity to a change in atmospheric carbon dioxide concentration. The authors consider two extreme climates, the Last Glacial Maximum 18,000 years ago and the mid-Cretaceous warm maximum (around 100 million years ago), each of which is characterized by differences in carbon dioxide relative to today.

Two types of information are essential in exploiting palaeoclimatic data in this way. First, the temperature of the Earth in each of the case studies must be reasonably established. At a minimum, the globally averaged surface temperature must be defined. But the seasonal and latitudinal distribution of temperatures would provide a firmer basis for interpretation of the results. Second, all the forcing factors (such as the concentration of greenhouse gases, changes in the Sun, aerosol content of the atmosphere, geography and vegetation) must be known. Lack of knowledge of any one significant climatic forcing factor would bias the estimate of the climate sensitivity to changes in carbon dioxide.

Obviously, estimation of any of these quantities for the past is associated with substantial uncertainty. For example, estimates of the globally averaged surface temperatures at the Last Glacial Maximum range from 3 to 5° C below the present-day average (15 °C); and mid-Cretaceous temperature estimates range from 6 to 12 °C higher. The distribution of polar ice at the Last Glacial Maximum, significant in defining the global albedo of the time, is still a matter of debate. The level of atmospheric carbon dioxide during the mid-Cretaceous is estimated to be anything from 2 to 11 times the present-day concentration. A value for the solar luminosity during the Cretaceous can be based on the evolution of that type of star, but this approach is basically unverified. In summary, neither the forcing factors nor the globally averaged surface temperatures are precisely defined for the past.

Hoffert and Covey confront these difficulties by using 'best' estimates of the temperatures and the forcing factors and then incorporating component uncertainties. From the best estimates, the Last Glacial Maximum and mid-Cretaceous yield climate sensitivities of 2.0±0.5 and 2.2±0.7 °C, respectively. Colder estimates of the glacial temperatures (5 °C lower than the present) would yield a sensitivity closer to 3.0 °C. But in short, the two eras yield sensitivities that are within the range cited by the IPCC. Certainly, the case studies suggest that the very low sensitivities suggested by some authors (such as Lindzen[2]) are not justified. But although the conclusions will be valuable in predicting the impact of fossil-fuel consumption and of the measured increase in atmospheric carbon dioxide, the precision of Hoffert and Covey's estimates should be treated with caution.

First, the authors' estimates of climate sensitivity fall within the lower half of the values generated by GCMs and cited in the IPCC report. Yet, so far not a single palaeoclimate simulation for the past has over-estimated the warming or cooling reconstructed from the geological data. In fact, palaeoclimatic simulations are notable in that they consistently underestimate the data, so that Hoffert and Covey may be underestimating climate sensitivity. The propensity of models to underestimate the data has prompted authors to speculate on the need to consider additional forcing factors, to re-evaluate the observations or to consider missing or inadequate feedback relationships in model construction. The explanation of this enigma may be that GCMs have rarely been applied to the past; simulations yet to be tried may give overestimates. But two other explanations are possible. Hoffert and Covey's estimates may be correct if the surface albedo changes (ice cover and so on) are specified for the past, but if these feedbacks are calculated as part of the climate response rather than specified, then the lack of model sensitivity becomes apparent. Alternatively, the inadequacies of estimates of model sensitivity derived from global temperatures may become apparent only when the comparisons of data and models are based on seasonal and latitudinal data, not averages.

Second, Hoffert and Covey consider only two case studies. At least two other periods, the Younger Dryas[3], at the end of the last ice age, and the Eocene[4], are thought to be characterized by very different climate roles for the deep ocean. The mid-Cretaceous may also be characterized by a reversal of the deep circulation in response to increased atmospheric carbon dioxide[5]. But GCMs used for the IPCC report do not incorporate any explicit role for the oceans.

Hoffert and Covey's study adds to the weight of evidence in support of the IPCC conclusions. However, until GCMs actually simulate past climates, or, better, overestimate past changes in climate, we cannot be completely certain that GCMs incorporate the full range of climate sensitivities recorded in the geological record. □

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