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REVIEWS

Warm Climates in Earth History

Edited by Brian T. Huber, Kenneth G. MacLeod and Scott L. Wing
Cambridge University Press,
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Global climate change and man's role in global warming is a contentious issue. By the end of the 21st century, CO_2 concentrations in the atmosphere are expected to be twice the pre-industrial level, and climate models predict that we will be entering a greenhouse climate. These concerns, together with results from more powerful computers running sophisticated simulations of modern climate, have sparked a great deal of interest in ancient global climates.

Most of the early research on climate change dealt with the glacial/interglacial cycles of the Quaternary, where the spatial and temporal resolution is very detailed, but fluctuations in climatic variables were relatively small. For example, the atmospheric CO_2 concentration during the last glacial maximum was only about 30% less than pre-industrial levels, which is about the same amount as the increase from pre-industrial levels caused by anthropogenic emissions during the last 125 years. Consequently, when added to the predicted doubling of pre-industrial levels by the end of the 21st century, the CO_2 concentrations reached during past glacial/interglacial cycles will be greatly exceeded. How can the significance of this prediction be assessed?

Computer models can simulate the effects of large fluctuations in climatic parameters but these outputs must be checked by empirical observations. This can only be done by studying paleoclimates in the older geologic record, where a much greater range of global climates is represented. The last 540 Ma was generally a warm period with minimal ice cover for about 75% of the time, and with several intervals of greenhouse climate where global CO_2 concentrations were well above the global CO_2 concentrations of Quaternary glacial/interglacial cycles. Estimates of ancient pCO_2 in the atmosphere are as high as double pre-industrial levels during the early Eocene, five times in the late Mesozoic, and twelve to eighteen times in the early Paleozoic.

Although warm climates were prevalent throughout the Phanerozoic, their causes, nature and mechanics are still poorly understood. Reconstructing global paleoclimates involves the interaction of two main approaches: computer simulations of atmospheric and oceanic circulation, and paleoclimatic reconstruction from various paleontological and geochemical proxy climate data. Theories of global climate (model simulations) require knowledge of the correct input variables, forcing mechanisms and feedback effects, which must be compared and tested by observations. Nonetheless, the oceanic and terrestrial data that provide climate proxy measures must also be valid. A lack of agreement means that there are still gaps in current understanding of greenhouse climates.

This volume describes a wide range of globally warm paleoclimates from the early Paleozoic to early Cenozoic, with a goal of providing a better understanding of the forcing mechanisms and feedbacks important in today's climate. To undertake this, the editors assembled a number of experts to describe their work in reconstructing paleoclimates during various parts of the Phanerozoic. When compared to the Quaternary, these ancient climates have poorer spatial and temporal resolution so that model outputs and proxy climate data often lead to conflicting conclusions. The stated objective of this book is to review recent developments in the study of ancient global climate and to show where proxy fossil and geochemical data and models agree and where problems still exist. Multiple lines of independent evidence are used to test results of numerical models. The editors' ultimate goal is to look for causes and consequences of past warm global climates and to find common links between warm periods in the geologic past.

The book is organized into five parts. Part I outlines the general elements of modern paleoclimatic studies in three chapters. The first chapter, by P.J. Valdes, is a good introduction to factors affecting global climate on long time scales. It describes the basic mechanics of climate, external forcing mechanisms (*e.g.*, solar luminosity) with internal feedbacks (ice cover, albedo).

In the second chapter, R.M. Deconto *et al.* review the basic approaches to climatic simulation and recent advances in modelling. Models have evolved from simple energy balance equations to sophisticated 3-D General Circulation Models (GCMs) that couple both atmospheric and oceanic general circulation models. Global climate is treated as an earth system by integrating the physical, chemical and biological systems into the whole. Some recent modelling advancements include the input of vegetation types and distribution, and atmosphere-vegetation interactions.

Recent improvements in models and more powerful computers are narrowing discrepancies between climate model outputs and geological observations. For example, early GCMs for the Eocene predicted seasonal freezing in the continental interior of North America. This was contradicted by paleontological data, which indicated mild winters through the presence of palm trees, crocodilians and other frost-intolerant organisms. However, more recent modelling with more accurate paleogeography (presence of large lakes) show mean annual temperatures in closer agreement with biological data.

In Chapter 3, T.J. Crowley and J.C. Zachos describe the most common proxy measures of paleoclimate, stable isotopes. Their discussion centers on the reliability of $\delta^{18}O$, the most common proxy measure of paleotemperature. Paleotemperature estimates from $\delta^{18}O$ do not always agree with other proxy measures. Although modern tropical sea surface temperatures (SSTs) are consistently around 24-28°C, estimates of ancient SSTs are much more variable. For example, based on $\delta^{18}O$, Eocene tropical SSTs ranged from 18°C to 24°C, but the distribution of Eocene reefs suggests that SSTs were similar to today. Similarly, Late Cretaceous isotopes suggest SSTs about 10°C below modern but studies on bivalves suggest similar temperatures to present. Possible sources of error may be diagenetic artifacts or due to salinity effects or secular variations in $\delta^{18}O_{\text{seawater}}$.

Parts II to IV of the book are case studies of progressively older warm intervals during the Phanerozoic. Various authors present geologic data and modelling results from different perspectives.

Part II describes the paleoclimates of the late Paleocene to early Eocene, geologic epochs having the most paleoclimatic information. K.L. Bice *et al.* (Chapter 4) discuss the fit between simulated global ocean temperatures and global paleotemperatures interpreted from oxygen isotopes of benthic and shallow-dwelling planktonic foraminifera for the early Eocene. There is usually good agreement for surface water paleotemperatures but modelled deep-water paleotemperatures are usually less than those indicated by the proxy data. Again, the importance of the stability in $\delta^{18}O_{\text{seawater}}$ may be a factor in resolving this issue.

E. Thomas *et al.* (Chapter 5) describe global paleoceanography from latest Paleocene to earliest Eocene based on paleontological and stable isotope data, with special reference to the latest Paleocene Thermal Maximum event. For the Eocene, R.D. Norris *et al.* (Chapter 6) describe continental paleotopographic reconstruction by estimating paleoaltitudes from stable isotopes. They conclude that in Eocene time the Laramide Mountains of Colorado were as high or higher than the present Colorado Rocky Mountains.

In the final chapter of Part II, S.L. Wing *et al.* (Chapter 7) show unexpected climatic variability during the strongest greenhouse interval of the last 65 Ma. Paleobotanical and geochemical records from the northern Rocky Mountains show a consistent cooling during the otherwise globally warm Eocene. The main tools used by Wing *et al.* are paleotemperatures derived from leaf margin analysis and oxygen isotope geochemistry. Leaf margin analysis recognizes that in modern populations of plants there is a strong positive correlation between the relative proportion of species with smooth leaf margins and the mean annual temperature. These data are used to interpret paleoclimate based on measurements of fossil plant communities. Oxygen isotopes were derived from $\delta^{18}O_{\text{hematite}}$ extracted from fossil mammal bones. Climatic dynamics of cold periods are likely very different from the warm periods this book highlights.

Part III covers extremely warm periods of the Mesozoic. K.G. MacLeod *et al.* (Chapter 8) describe the global distribution of deep sea inoceramid bivalves throughout the Late Cretaceous and compare this to parallel studies of stable isotope data and changes in oceanic circulation. They use their data to postulate a model of oceanic circulation with poleward heat transport by saline water masses.

Recent computer modelling of climate, vegetation and ocean interactions is described by R.M. DeConto *et al.* in Chapter 9. They reconstruct the Campanian (80 Ma) climate by modelling elevated pCO_2 and oceanic heat transport, including a predictive vegetation model that allows climate and vegetation to interact through feedback loops. It appears that vegetation may have played an essential role in maintaining low meridional thermal gradients during the Cretaceous. Proxy data usually show that greenhouse climates characteristically have a reduced equator to pole temperature gradient; whereas computer models consistently show greenhouse climates with accurate mean global temperatures but with warmer tropics and colder poles. These discrepancies are also prevalent when comparing empirical data and model outputs for the Jurassic, as shown by P.McA. Rees *et al.* (Chapter 10). In dealing with Jurassic plant assemblages, Rees *et al.* describe a new method of evaluating floristic data quantitatively and interpreting climatically sensitive sediment types such as evaporites and coals. In general, warm stable climatic conditions are indicated during this time.

Part IV depicts the main warm intervals of the Paleozoic. Unlike models of more recent climates, models of early Paleozoic climates must assume significantly lower solar luminosity, much higher pCO_2 (ten to eighteen times) and negligible vegetation on land. In Chapter 11, E.L. Taylor *et al.* describe extremely well-preserved cellular structures in Permian and Jurassic wood from Antarctica. They show convincingly that the climate of the South Pole was warmer and seasonally less extreme than current modeling outputs indicate. They suggest that disagreement between their data and models may be due to inaccurate inputs of albedo and topography. In Chapter 12, A.E. Murphy *et al.* describe greenhouse climates of Middle to Late Devonian time when prolonged extinction of shallow marine invertebrates occurred, and discuss the link between marine biogeochemical cycles, benthic community dynamics and climate. In the final chapter of this section, M.T. Gibbs *et al.* (Chapter 13) discuss parallel climate simulations of Late Ordovician (glacial) and Early Silurian (non-glacial/greenhouse) paleoclimates to determine the relative importance of paleogeography and pCO_2 in forcing the transition from greenhouse to icehouse global climatic states. The relative stability of the greenhouse state is also assessed.

In Part V, the final section of the

book , T.J. Crowley (Chapter 14) provides an overview of all Phanerozoic climates and discusses the relative importance of different forcing mechanisms in his opinion. Overall there is a strong correlation between pCO_2 and the state of global climate, but paleogeography and solar luminosity are also critical factors. Orography, ocean heat transport, vegetation and system instabilities in climate are considered secondary factors that act as internal feedbacks. These internal feedbacks are thought to be most important when global climate system is at a bifurcation point.

The conclusion imparted by this book is that the broad patterns characterizing greenhouse climates are generally accepted, but there is still much more to do before theory and geological data converge. Better proxy data and models have resolved some of the controversies but certain areas are still poorly understood. Geochemical and paleontological data consistently show a reduced equator-to-pole temperature gradient and much warmer winter temperatures in the mid to high latitude continental interiors, which the models fail to reproduce. The book concludes that these problems will eventually be resolved with larger and better-defined proxy data sets (fossil, geochemical, paleogeographical) coupled with better models (atmospheric-ocean dynamics) on finer spatial and temporal scales.

A common theme throughout this book is reconciling theories of global climate based on simulations *versus* observation of past terrestrial and marine paleoenvironments. If the models do not agree with the observations, then either the models need further refinement or the proxy measure of paleoclimate is inaccurate; throughout the book, it seems that certain authors favour one or the other depending on their background. It can be argued that not until theory and observations are in complete agreement will the processes underlying warm earth phenomena be truly known.

One aspect of the climate that this book does not fully address is that the climate system probably is non-linear. If the climate system behaves chaotically, are current modelling predicitions valid? As Crowley points out in Chapter 14, if global climate happens to be at a bifurcation point, then secondary feedback effects come into play. However, if such a metastable system were subjected to a catastrophe, such as an extraterrestrial impact event, what would be the consequences? Another aspect not addressed is the possible role that gas-hydrate reservoirs may have on the global carbon cycle and climate stability.

This is an excellent volume for researchers or students seeking an introduction to paleoclimatology of the deep past. The volume would also make a good reference book with extensive references and a good index. Although some of the black and white line drawings are poorly reproduced, overall production quality is very good, with excellent black and white photographs and colour drawings, and no typographical errors to be found.

Billion-year Earth History of Australia and Neighbours in Gondwanaland

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The recent Olympics drew a lot of attention to the scenic splendors of Australia. Many of these tourist attractions, such as the famous Uluru (Ayers Rock) and Sydney Harbour, also contain an equally amazing record of geological history. For instance, the pristine sandstone that forms the harbourside cliffs and hills that gold medallist triathlete Simon Whitfield successfully swam, biked and ran past may have originated in Antarctica when that continent was still the mountainous heart of Gondwanaland. Such speculative provenance and more Australian geology than you can point a boomerang at are presented in the detailed and meticulously illustrated *Billion-year Earth History of Australia and Neighbours in Gondwanaland* (*BYEHA*). *BYEHA* is the successor to the 1984 compilation *Phanerozoic Earth History of Australia* and follows a similar format. Discussion is divided into 26 semi-independent chapters by various authors, including key sections by John Veevers. The chapters are collated into three parts. The first, "Present and Past Global Settings," contains up-to-date discussions of paleomagnetic, seafloor spreading and morphotectonic data. The second part, "Analysis of Australia," contains descriptions of the present Australian crust and lithosphere from a broad range of disciplines, including data from seismic interpretations, mantle xenoliths, heat flow and detrital zircons. The second part also provides an up-to-date review of the Neoproterozoic history of Australia, including data of relevance to the emerging Snowball Earth hypothesis.

The third part, "Regional Synthesis," contains discussion of direct interest to Canadian readers: Neoproterozoic Australia-Laurentia connections. After a few blunt words about the over-reliance of various Rodinia hypotheses on paleomagnetic data, Veevers discusses an alternative approach of examining Australia-Laurentia connections in the framework of Pangean supercontinent cycles. Rather than rely on physical connections, the similarities of certain features and sequences between Australia and Laurentia are thought to reflect a common cyclic history of subsidence, magmatism and rifting as Pangea formed and dispersed three times during the last billion years. Given the similar continental scale of Canadian geology, there may be great potential here for confirming or challenging Veevers's global hypotheses.

The sheer amount of information, particularly in some figures, and the occasional irksome need to flick between discussion and figures on widely separate pages can be frustrating for a new reader. This is not a geology textbook with glossy diagrams and sidebars. *BYEHA* is a comprehensive compilation of the current understanding of post-Mesoproterozoic Australian geology. If anything, the