PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

A Brief Discussion of the History, Strengths and Limitations of Conceptual Climate Models for Pre-Quaternary Time

Judith Totman Parrish

Phil. Trans. R. Soc. Lond. B 1993 **341**, 263-266
doi: 10.1098/rstb.1993.0111

A brief discussion of the history, strengths and limitations of conceptual climate models for pre-Quaternary time

JUDITH TOTMAN PARRISH

Department of Geosciences, Gould-Simpson Building, University of Arizona, Tucson, Arizona 85721, U.S.A.

SUMMARY

Although it has been recognized at least since the time of Darwin and Agassiz that climate has varied significantly over geologic time, the study of global palaeoclimate did not come into its own until the theory of continental drift became ascendant. Initial studies in the early 1960s used climate models to test the reconstructions of continental positions. These studies, many collected in a pair of symposium volumes edited by A. E. M. Nairn, used a zonal model of climate or simple modifications thereof to predict how certain palaeoclimatic indicators – principally evaporites, coals, carbonates, red beds, and eolian sandstones – should be distributed on the continents through time if the continental reconstructions were correct. Even at that early stage in the development of continental reconstructions, past patterns of sedimentation were more clearly explained than had previously been the case.

Continental reconstructions eventually began to stabilize, at least with respect to the major plates, in the late 1970s. Most of the information for positioning the continents came from paleomagnetic and structural data, but some elements of continental reconstructions relied heavily on climatic data – and the zonal climate model – for positioning. Nevertheless, it was at this time that studies of global palaeoclimate, independent of the concerns about the positions of the continents, could begin in earnest. A primary need was independence of the continental reconstructions from palaeoclimatic data, an ideal even now fully realized only for the late Mesozoic and Cenozoic.

The term 'conceptual climate model' was coined by J. E. Kutzbach in reference to models published in the early 1980s. Like numerical models, conceptual climate models are based on the fundamentals of atmospheric circulation as determined from studies of the modern climate system, without explicitly treating atmospheric dynamics. They are reproducible and useful for developing an understanding of major changes in climate patterns driven by the changing positions of the continents. Despite their simplicity and non-explicit treatment of atmospheric dynamics, conceptual climate models have proved to be surprisingly robust in that the patterns predicted by explicitly dynamical models are similar for any given geologic period.

Global palaeoclimate has long been of interest to geologists. In the early 1800s, Agassiz (1828) and Darwin (1842) recognized that climate has varied significantly over geologic time in different parts of the world. In the late 1800s, Chamberlin (1897, 1899*a–c*) discussed the possible climatic influences of changing atmospheric concentrations of carbon dioxide, particularly in reference to the Ice Ages. Chamberlin's work foresaw much of the work on carbon dioxide that is so important today. Croll (1875, in Brooks 1949) anticipated later quantitative work on variations in the Earth's orbital parameters and their effect on climate change.

The most prescient of the early works on pre-Quaternary paleoclimate was the treatment by Köppen & Wegener (1924), *Die Klimate der geologischen Vorzeit*, which combined Köppen's simplified models of zonal climate with the continental drift hypotheses of Wegener. This work was analysed by the geographer, C. E. P. Brooks (1926, revised 1949), in a comprehensive analysis of evidence for palaeoclimates. Brooks (1949) noted that '. . . palaeoclimatological evidence plays a considerable part in the working out of the theory [on continental drift], which in turn, if accepted, completely alters the aspect of the problem of climatic changes. . . '. Brooks (1949) was extremely critical of Köppen & Wegener (1924), pointing out a number of discrepancies in their arguments, and concluded that the preponderance of evidence supports a static world. This so-called 'fixist' view of global palaeoclimate also was adhered to by Matthew (1939), who studied the distributions of vertebrates, but was opposed by Ma (1937), who worked on Chinese corals.

Part of the rationale for the theory of continental drift was the evidence of dramatic changes in climate during Earth history in parts of the world. Such evidence required that either (i) climate patterns have changed dramatically during Earth history, or (ii) the continents had moved. Köppen & Wegener (1924)

Phil. Trans. R. Soc. Lond. B (1993) **341,** 263–266
Printed in Great Britain

settled on the latter explanation, Brooks (1949) on the former. In fact, there was a third and more likely possibility, namely, that the continents had moved and that climate had changed dramatically. Interestingly, the period on which Brooks (1949) focused most closely – Late Carboniferous and Permian – was such a time, and thus was an unfortunate, if logical, choice.

The study of pre-Quaternary global palaeoclimate did not begin to come into its own until the theory of continental drift became ascendant. The most significant initial studies appeared in the early 1960s in a pair of symposium volumes edited by A. E. M. Nairn (Nairn 1961*a*, 1964). These studies fell into three categories: (i) outlines of the palaeoclimatic history of certain time intervals or certain parts of the world; (ii) discussions of the climatic significance of various rocks and fossils, such as red beds and plants (Kräusel 1961; Van Houten 1961, 1964; Dorf 1964); and (iii) reconstructions of continental plate positions based on palaeoclimatic data (e.g. Briden & Irving 1964; Nairn & Thorley 1961). The thrust of many of these studies, particularly in the 1964 volume, and of many subsequent papers in this vein (Briden 1968, 1970; Drewry *et al.* 1974), was to use climate models and palaeoclimate data to test the reconstructions of continental positions that were based on palaeomagnetism. The reader will recall that the use of palaeomagnetism to reconstruct continental positions and, indeed, the entire theory of continental drift, were being actively studied at this time. The history leading to the volumes edited by Nairn is fully discussed by him (Nairn 1961*b*) and by Bucher (1964).

The studies that used palaeoclimate to try to interpret continental reconstructions employed a zonal model of climate – a generalization of modern climate patterns into zones or belts parallel to latitude – or simple modifications of the zonal model. The zonal model was used to predict how certain palaeoclimatic indicators – principally evaporites, coals, carbonates, red beds, and eolian sandstones – should be distributed on the moving continents through time (Briden & Irving 1964; Bucher 1964). Even at that early stage, in the 1960s, in the development of continental reconstructions, many past patterns of sedimentation were more clearly explained than had previously been the case. Interestingly, continental drift reconstructions were not rejected for the late Paleozoic and early Mesozoic – the interval during which the supercontinent existed – despite the fact that the sedimentation patterns and reconstructions did not seem to fit (Briden & Irving 1964; Drewry *et al.* 1974; Stehli 1968, 1970). This was the interval on which Brooks (1949) had focused; subsequently it has been shown that climate was probably least zonal at that time (e.g. Parrish *et al.* 1982).

The aforementioned quote from Brooks (1949) raised an issue that has plagued global palaeoclimatology, and even now has not been completely eradicated (e.g. Witzke 1990; Scotese & Barrett 1990). The problem is one of circular reasoning, and was at the time impossible to escape. Eventually, however, continental reconstructions began to stabilize, at least with respect to the configuration of the major plates, in the late 1970s. Most of the data used to position the plates came from palaeomagnetism and structural geology, but some elements of continental reconstructions still relied heavily on the distribution of climatic indicators – and the zonal climate model – for positioning (e.g. Heckel & Witzke 1979). Nevertheless, it was at this time that studies of global palaeoclimate, independent of the concerns about the positions of the continents, could begin in earnest. A primary need was independence of the continental reconstructions from palaeoclimatic data, an ideal even now fully realized only for the late Mesozoic and Cenozoic.

The term 'conceptual climate model' was coined by J. E. Kutzbach in reference to models published in the early 1980s (Parrish & Curtis 1982; Parrish 1982; Lloyd 1982), but these were by no means the first such models employed in palaeoclimatology. The zonal climate model, used to predict the distribution of climatic indicators with the purpose of testing continental reconstructions, also falls into that category. Like numerical models, conceptual climate models are based on some understanding of the fundamentals of atmospheric and oceanic circulation as determined from studies of the modern system. However, the conceptual models predict only patterns of climate – atmospheric pressure, wind directions, precipitation – without explicitly treating atmospheric or oceanic dynamics. Conceptual models employed before 1982 include, for example, those by Gordon (1973) to investigate possible Cretaceous ocean circulation patterns; Ross (1975) to investigate the distributions of Ordovician trilobites; Nairn & Smithwick (1976), who were interested in the strange climate of the supercontinent Pangea in the Permian; and Ziegler *et al.* (1977), who combined information on biogeographic and sedimentologic indicators of Silurian climate. Dott (1979) and Drewry *et al.* (1974) used all or parts of the zonal model to study the distribution of tropical and global climatic indicators, respectively. In addition to models by Parrish (1982; Parrish & Curtis 1982; Parrish *et al.* 1982; and later papers), conceptual models of varying complexity have been used since 1982 by Marsaglia & Klein (1983), Witzke (1990), and Boucot & Gray (1983), among others. Semi-quantitative, non-dynamical climate models have been constructed by Scotese & Summerhayes (1986) and Gyllenhaal *et al.* (1991).

Conceptual models are reproducible and useful for developing an understanding of major changes in climate patterns driven by the changing positions of the continents. Despite their simplicity and non-explicit treatment of atmospheric dynamics, well-founded conceptual models have proved to be surprisingly robust in that the climate patterns are similar to those predicted by numerical models for any given geologic period. Compare, for example, the conceptual atmospheric and oceanic circulation models of Parrish for the Permian and Triassic (Parrish & Curtis 1982; Ziegler *et al.* 1981) with the numerical model results for Pangea by Kutzbach (Kutzbach & Gallimore 1989; Kutzbach *et al.* 1990).

Recent developments in numerical modeling are rapidly obviating the need for conceptual models, which have, among other advantages, those of being inexpensive and quick to produce. One such development is the attention given to Pangean climates by a number of groups using different models, which will facilitate comparisons of numerical models (Kutzbach & Gallimore 1989; Chandler *et al.* 1992; Crowley *et al.* 1989; Valdes & Sellwood 1992; Thompson *et al.* 1992). Another development is that desktop versions of some numerical models are making the models accessible to more users (e.g. Thompson *et al.* 1992).

REFERENCES

Agassiz, L. 1828 On the erratic blocks of the Jura. *Edinb. New Phil. J.* **24**, 176–179.

Boucot, A.J. & Gray J. 1983 A Paleozoic Pangaea. *Science, Wash.* **222**, 571–581.

Briden, J.C. 1968 Paleoclimatic evidence of a geocentric axial dipole field. In *The history of the Earth's crust* (ed. R. A. Phinney), pp. 178–194. Princeton University Press.

Briden, J.C. 1970 Palaeolatitude distribution of precipitated sediments. In *Palaeogeophysics* (ed. S. K. Runcorn), pp. 437–444. London: Academic Press.

Briden, J.C. & Irving, E. 1964 Paleolatitude spectra of sedimentary paleoclimatic indicators. In *Problems in paleoclimatology* (ed. A. E. M. Nairn), pp. 199–224. London: Interscience Publishers.

Brooks, C.E.P. 1949 *Climate through the ages*. London: Ernest Benn Ltd.

Bucher, W.H. 1964 The third confrontation. In *Problems in palaeoclimatology* (ed. A. E. M. Nairn), pp. 3–9. London: Interscience Publishers.

Chamberlin, T.C. 1897 A group of hypotheses bearing on climatic changes. *J. Geol.* **5**, 653–683.

Chamberlin, T.C. 1899*a* An attempt to frame a working hypothesis of the cause of glacial periods on an atmospheric basis. *J. Geol.* **7**, 545–584.

Chamberlin, T.C. 1899*b* An attempt to frame a working hypothesis of the cause of glacial periods on an atmospheric basis – Special application of the hypothesis to the known glacial periods. *J. Geol.* **7**, 667–685.

Chamberlin, T.C. 1899*c* An attempt to frame a working hypothesis of the cause of glacial periods on an atmospheric basis. III. Localization of glaciation. *J. of Geol.* **7**, 751–787.

Chandler, M.A., Rind, D. & Ruedy, R. 1992 Pangaean climate during the Early Jurassic: GCM simulations and the sedimentary record of paleoclimate. *Geol. Soc. Am. Bull.* **104**, 543–559.

Croll, J. 1875 *Climates and time in their geological relations*. London.

Crowley, T.J., Hyde, W.T. & Short, D.A. 1989 Seasonal cycle variations on the supercontinent of Pangaea: implications for Early Permian vertebrate extinctions. *Geology* **17**, 457–460.

Darwin, C.R. 1842 Notes on the effects produced by ancient glaciers of Caernarvonshire, and on the boulders transported by floating ice. *Lond. Edinb. Dubl. phil. Mag.* **21**, 180–188.

Darwin, C.R. 1848 On the transportal of erratic boulders from a lower to a higher level. *Q. Jl geol. Soc. Lond.* **4**, 315–323.

Dorf, E. 1964 The use of fossil plants in palaeoclimatic interpretations. In *Problems in palaeoclimatology* (ed. A. E. M. Nairn), pp. 13–31. London: Interscience Publishers.

Dott, R.H. 1979 Paleolatitude and paleoclimate. *Trans. Wisconsin Acad. Sci. Arts Lett.* **67**, 4–13.

Drewry, G.E., Ramsay, A.T.S. & Smith, A.G. 1974 Climatically controlled sediments, the geomagnetic field, and trade wind belts in Phanerozoic time. *J. Geol.* **82**, 531–553.

Gordon, W.A. 1973 Marine life and ocean surface currents in the Cretaceous. *J. Geol.* **81**, 269–284.

Gyllenhaal, E.D., Engberts, C.J., Markwick, P.J. *et al.* 1991 The Fujita–Ziegler model: a new semi-quantitative technique for estimating paleoclimate from paleogeographic maps. *Palaeogeogr. Palaeoclim. Palaeoecol.* **86**, 41–66.

Heckel, P.H. & Witzke, B.J. 1979 Devonian world palaeogeography determined from distribution of carbonates and related lithic palaeoclimatic indicators. *Spec. Pap. Palaeont.* **23**, 99–123.

Köppen, A. & Wegener, A. 1924 *Die Klimate der geologischen Vorzeit*. Berlin: Borntraeger.

Kräusel, R. 1961 Palaeobotanical evidence of climate. In *Descriptive palaeoclimatology* (ed. A. E. M. Nairn), pp. 227–254. New York: Interscience Publishers.

Kutzbach, J.E. & Gallimore, R.G. 1989 Pangean climates: megamonsoons of the megacontinent. *J. geophys. Res.* **94**, 3341–3357.

Kutzbach, J.E., Guetter, P.J. & Washington, W.M. 1990 Simulated circulation of an idealized ocean for Pangaean time. *Paleoceanography* **5**, 299–317.

Lloyd, C.R. 1982 The Mid-Cretaceous Earth: paleogeography; ocean circulation and temperature; atmospheric circulation. *J. Geol.* **90**, 393–413.

Ma, T.Y.H. 1937 On the seasonal growth in Palaeozoic tetra corals and the climate during the Devonian Period. *Paleont. Sinica* B **2(III)**.

Marsaglia, K.M. & Klein, G.D. 1983 The paleogeography of Paleozoic and Mesozoic storm depositional systems. *J. Geol.* **91** (2), 117–142.

Matthew, W.D. 1939 *Climate and evolution*, 2nd edn. Special Publication of the New York Academy of Sciences, **1**.

Nairn, A.E.M. 1961*a* *Descriptive palaeoclimatology*. New York: Interscience Publishers.

Nairn, A.E.M. 1961*b* The scope of palaeoclimatology. In *Descriptive palaeoclimatology* (ed. A. E. M. Nairn), pp. 1–7. New York: Interscience Publishers.

Nairn, A.E.M. 1964 *Problems in palaeoclimatology*. London: Interscience Publishers.

Nairn, A.E.M. & Smithwick, M.E. 1976 Permian paleogeography and climatology. In *The Continental Permian in Central, West, and South Europe* (ed. H. Falke), pp. 283–312. Boston: D. Reidel Publishing Company.

Nairn, A.E.M. & Thorley, N. 1961 The application of geophysics to palaeoclimatology. In *Descriptive palaeoclimatology* (ed. A. E. M. Nairn), pp. 156–182. New York: Interscience Publishers.

Parrish, J.T. 1982 Upwelling and petroleum source beds, with reference to the Paleozoic. *Am. Ass. Petrol. Geol. Bull.* **66**, 750–774.

Parrish, J.T. & Curtis, R.L. 1982 Atmospheric circulation, upwelling, and organic-rich rocks in the Mesozoic and Cenozoic Eras. *Palaeogeogr. Palaeoclim. Palaeoecol.* **40**, 31–66.

Parrish, J.T., Ziegler, A.M. & Scotese, C.R. 1982 Rainfall patterns and the distribution of coals and evaporites in the Mesozoic and Cenozoic. *Palaeogeogr. Palaeoclim. Palaeoecol.* **40**, 67–101.

Ross, R.J., Jr. 1975 Early Paleozoic trilobites, sedimentary facies, lithospheric plates, and ocean currents. *Fossils Strata.* **4**, 307–329.

Scotese, C.R. & Barrett, S.F. 1990 Gondwana's movement over the South Pole during the Palaeozoic: evidence from lithological indicators of climate. In *Palaeozoic palaeogeography and biogeography* (ed. W. S. McKerrow & C. R. Scotese), pp. 75–85.

Scotese, C.R. & Summerhayes, C.P. 1986 Computer model of paleoclimate predicts coastal upwelling in the Mesozoic and Cenozoic. *Geobyte* **1**, 28–42.

Stehli, F.G. 1968 A paleoclimatic test of the hypothesis of an axial dipolar magnetic field. In *The history of the Earth's crust* (ed. R. A. Phinney), pp. 195–207. Princeton University Press.

Stehli, F.G. 1970 A test of the Earth's magnetic field during Permian time. *J. geophys. Res.* **75**, 3325–3342.

Thompson, S.L., Pollard, D., Hay, W.W. *et al.* 1992 Simulations of Triassic climate using a global circulation climate model (abs.). *Project Pangea Workshop, May 23–28, 1992, Lawrence*, Kansas p. 26.

Valdes, P.J. & Sellwood, B.W. 1992 A palaeoclimate model for the Kimmeridgian. *Palaeogeogr. Palaeoclim. Palaeoecol.* **95**, 45–72.

Van Houten, F.B. 1961 Climatic significance of red beds. In *Descriptive palaeoclimatology* (ed. A. E. M. Nairn), pp. 89–139. New York: Interscience Publishers.

Van Houten, F.B. 1964 Origin of red beds – some unsolved problems. In *Problems in palaeoclimatology* (ed. A. E. M. Nairn), pp. 647–661. London: John Wiley and Sons.

Witzke, B.J. 1990 Palaeoclimatic constraints for Palaeozoic palaeolatitudes of Laurentia and Euramerica. In *Palaeozoic palaeogeography and biogeography* (ed. W. S. McKerrow & C. R. Scotese), pp. 57–73.

Ziegler, A.M., Bambach, R.K., Parrish, J.T. *et al.* 1981 Paleozoic biogeography and climatology. In *Paleobotany, paleoecology, and evolution*, vol. 2 (ed. K. J. Niklas), pp. 231–266. New York: Praeger Publishers.

Ziegler, A.M., Hansen, K.S., Johnson, M.E. *et al.* 1977 Silurian continental distributions, paleogeography, climatology, and biogeography. *Tectonophysics* **40**, 13–51.