3 Bostrom, K., and Peterson, M. N. A., *Mar. Geol.*, **7**, 427 (1969).
4 von der Borch, C. C., and Rex, R. W., *Init. Rep. Deep Sea Drilling Project*, **5**, 541 (US Govt Printing Office, Washington, 1970).
5 Corliss, J. B., *J. geophys. Res.*, **76**, 8128 (1971).
6 Bender, M., *et al.*, *Earth planet. Sci. Lett.*, **12**, 425 (1971).
7 Bonatti, E., Kramer, T., and Rydell, H., in *Papers from a Conference on Ferromanganese Deposits on the Ocean Floor* (edit. by Horn, D. R.), 149 (IDOE/NSF, Washington, 1972).
8 Herron, E. M., *Geol. Soc. Am. Bull.*, **83**, 1671 (1972).
9 Dymond, J., Corliss, J. B., Heath, G. R., Field, C. W., Dasch, E. J., and Veeh, H. H., *Geol. Soc. Am. Bull.*, **84**, 3355 (1973).
10 Anderson, R. N., and Halunen, A. J., Jr, *Nature*, **251**, 473 (1974).
11 Goldberg, E. D., and Koide, M., *Geochim. cosmochim. Acta*, **26**, 417 (1962).
12 Ku, T.-L., Broecker, W. S., and Opdyke, N., *Earth planet. Sci. Lett.*, **4**, 1 (1968).
13 Ku, T.-L., Bischoff, J. L., and Boeesma, A., *Deep Sea Res.*, **19**, 233 (1972).
14 Bostrom, K., Kramer, T., and Gartner, G., *Chem. Geol.*, **11**, 123 (1973).
15 Piper, D. Z., *Earth planet. Sci. Lett.*, **19**, 75 (1973).
16 Cronan, D. S., and Garrett, D. E., *Nature phys. Sci.*, **242**, 88 (1973).
17 El Wakeel, S. K., and Riley, J. P., *Geochim. cosmochim. Acta*, **25**, 110 (1961).
18 Bender, M., Ku, T.-L., and Broekcer, W. S., *Earth planet. Sci. Lett.*, **8**, 143 (1970).
19 McMurtry, G. M., *Geol. Soc. Am. Abstr. with Programs*, **6**, 218 (1974).

Long term variations in the albedo and surface temperature of the Earth

THE surface temperature of the Earth depends primarily on the solar constant, the Earth's albedo and the total mass and chemical composition of the terrestrial atmosphere. Studies of climate covering the past few million years have generally allowed for variations in albedo in calculating average values of the surface temperature. But over longer periods of time, however, less allowance has been made for albedo variations; it has, indeed, frequently been assumed that the albedo, when averaged over a long enough time, can be taken to be constant (see ref. 1). We wish to point out that, on the contrary, long term variations in the albedo can be expected to occur, and to produce significant changes in the average surface temperature.

The total albedo of the Earth depends on the relative proportions and dispositions of the continents and oceans and their related cloud covers. This varies both because the cross section presented to incident solar radiation by a given area depends on its latitudinal position, and because the variation in reflectivity with angle of incident radiation changes from land to ocean. Throughout much of the geological record, the relative amounts of continent and ocean do not seem to have undergone major change; but the relative disposition of the two has varied considerably because of continental drift. The amount of land area, as distinct from continental area, has certainly undergone fluctuations, but no systematic trend appears either in time, or relative to the disposition of the continents on the Earth's surface. We have estimated the average surface temperature of the Earth using a computer program which allows both for the greenhouse effect of the atmosphere and for variations in albedo resulting from different positions of the continental masses, but which assumes no significant change in the ratio of land-to-ocean area. (Surface temperatures have been computed as a function of latitude for land and ocean separately, and an average, weighted according to the areas involved, has then been calculated.)

If cloud cover is initially ignored, the important factor is the latitudinal distribution of the continents. We have therefore looked especially at two extreme cases: (1) where the continents are gathered together into a belt round the equator; (2) where they form a cap round one, or both, poles. We have constructed semi-empirical curves of reflectivity as a function of the angle of incident radiation, assuming in case (1) a covering of soil, and in case (2) an ice–snow covering. Although considerable information is available on the albedo of different types of surface, data on the variation of albedo with solar elevation are less well determined[2]. Fortunately, computer runs using a range of possible albedo variations with angle indicate that only minor changes are produced in the surface temperature with any reasonable functional relationship. The difference in albedo between the two models is found to change the surface temperature by more than 12 °C (the higher temperature corresponding to the equatorial position of the continents). Since the difference between a glacial and an interglacial period probably corresponds to a change in average temperature of only 5 °C (ref. 3), this albedo-dependent variation must be regarded as significant.

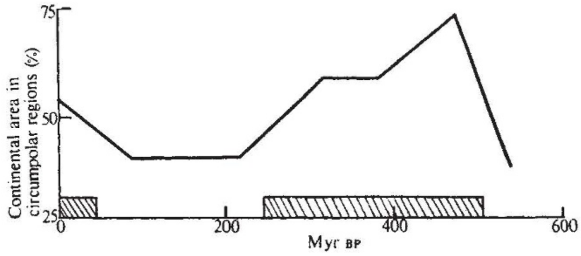

Fig. 1 Variation of continental area within 30° of poles as a function of time. The shaded parts of the time axis include all extensive glaciations[4,5].

There are, however, two modifications that should be made. First, we have assumed extreme dispositions of the land-masses in deriving this figure for the surface temperature. More probable variations in the latitudinal position of the centre of area of the continents will still lead to differing values of the albedo, and therefore to differences in surface temperature, but the change will be smaller than that derived above. Similarly, the effect of introducing cloud cover into the calculations, for any likely cloud distribution, is to reduce the change in albedo and so the variation in surface temperature. Nevertheless, after allowing for both these factors, the amount of latitudinal change postulated in reconstructions of continental drift still seems from our estimates to be capable of producing a variation in surface temperature of a few degrees. The effect of this would be to accentuate the prevailing climatic conditions. In particular, although a land-mass near one of the poles would, in any case, be expected to have an ice–snow cover, a resultant slight lowering of the average temperature, as a result of the albedo effect, could turn this into a major glaciation. The effects of this could then extend to appreciably lower latitudes than would otherwise be the case. Whether or not this occurs will depend on other astronomical and geological factors. What we can assert is a statement of probability: that the likelihood of extensive glaciation occurring should be greater when a higher proportion of the land mass is near the poles.

We have used the data cited by McElhinny[4] to derive values for the latitudinal distribution of the continents during each geological period. The results are best represented in terms of the percentage of the terrestrial surface within 30° of each pole which is covered by continent. The reason for choosing this form of presentation for the data is that continental displacements at lower latitudes, although leading to small changes in the albedo, cannot support extensive glaciation. It is the latter that can most readily be detected in the geological record.

Some of the data on continental drift remain uncertain. In particular, information on continental drift and major glaciations in the Precambrian is still inadequate for the type of comparison we wish to make here. Nevertheless, as can be seen from Fig. 1, if we separate out the periods during which extensive glaciations most commonly occurred[5], these correlate reasonably well with periods when a higher percentage of the circumpolar regions was occupied by continents. Within the limits of accuracy of the data, therefore, predictions based on the albedo effect are supported by the available geological evidence.

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1 Sagan, C., and Mullen, G., *Science*, **177**, 52 (1972).
2 Robinson, N. (ed.), *Solar Radiation*, ch. 6 (Elsevier, Amsterdam, 1966).
3 Bryson, R. A., *Science*, **184**, 753 (1974).
4 McElhinny, M. W., *Palaeomagnetism and Plate Tectonics* (Cambridge University Press, 1973).
5 Seyfert, C. K., and Sirkin, L. A., *Earth History and Plate Tectonics*, 455 (Harper and Row, New York, 1973).