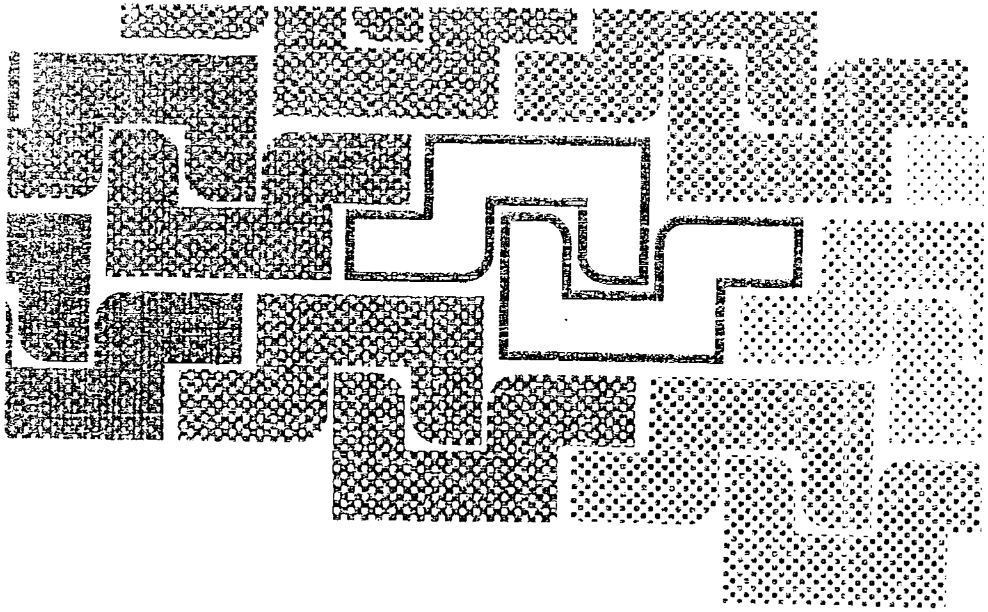

Milankovitch and Climate

Part 2

edited by A. Berger, J. Imbrie,
J. Hays, G. Kukla, and B. Saltzman

NATO ASI Series

Series C: Mathematical and Physical Sciences Vol. 126

INSOLATION GRADIENTS AND THE PALEOCLIMATIC RECORD

M.A. Young and R.S. Bradley

Department of Geology and Geography
University of Massachusetts
Amherst, MA 01003, USA

ABSTRACT

Hemispheric insolation gradients play an important role in driving the global atmospheric circulation, and may have contributed to the growth and decline of continental ice sheets by modulating the transport of moisture to high latitudes. Mid-monthly insolation differences between 30° and 90° latitude in each hemisphere were computed at 1000 years intervals for the past 150 000 years. Times of rapid ice build-up correpond to a distinctive seasonal pattern of insolation gradient deviations, with generally high gradients throughout the year, and follow closely times of strong autumn insolation gradients. The opposite patterns are observed at times of ice wastage.

INTRODUCTION

Throughout the development of the Milankovitch theory of climatic change, attention has focused on the insolation at critical latitudes and seasons which were thought to be particularly sensitive to glacierization and eventual ice sheet growth. In this paper, we will emphasize the more global view of orbitally-induced radiation variations that can be obtained by considering insolation gradients over substantial bands of latitudes.

Both insolation gradients and the boundary conditions on the climatic system (e.g. the presence or absence of ice sheets) influence hemispheric temperature gradients, which themselves are a major factor in determining the intensity of the extra-

A. L. Berger et al. (eds.), Milankovitch and Climate, Part 2, 707–713.

tropical atmospheric circulation. Several authors (e.g. 1,2) have examined these relationships and there is a consensus that stronger insolation gradients result in the displacement of the sub-tropical highs toward the equator, a more intense circumpolar westerly flow, and increased moisture transport to high latitudes. In contrast, weaker insolation gradients have the opposite effects, with a reduction in the moisture flux to artic and sub-artic regions. Berger (3) has suggested that the seasonal variation of the insolation gradient between 10 and 60°N, with its related poleward atmospheric transport of sensible and latent heat, provides a signature for the initiation of glacial and interglacial stages. Kutzbach, et al. (4) have also argued that the magnitude of astronomically-driven changes in insolation gradients is great enough to have produced significant climatic responses. Here, we make some simple time-domain comparisons between insolation gradient variations and the paleoclimatic record.

CIRCULATIONS, RESULTS, AND PALEOCLIMATIC COMPARISONS

The difference between mid-monthly insolation values at 30° and 90° latitude (hereafter referred to as the 30-90° insolation gradient) were computed for each hemisphere, at 1000 year intervals, over the past 150 kyr using the algorithm of Berger (5). Values are reported in units of W/m^2 ($1\ W/m^2 = 2.06$ ly/day). Very similar results, qualitatively, were obtained for the 20-70° and 30-60° latitude bands in the northern hemisphere. Because the mid-monthly insolation values are based on constant true solar longitudes (0=March, 30=April, etc.), the length of time between successive monthly positions varies somewhat as the location of perihelion slides along the orbit. Despite this, we prefer this option over the calendar date option which artificially accomodates most of variation in the lengths of the astronomical seasons during the months around the autumnal equinox.

Contour plots of the deviations of the monthly gradient values from the appropriate monthly 150 kyr means are presented in Figure 1. A strong ∿23 kyr periodicity dominates the winter insolation gradients in each hemisphere, while the summer gradients exhibit fairly pure, though smaller amplitude, 40 kyr signals. Unlike insolation deviations, which must sum to approximately zero when all latitudes and seasons are considered, it is clear from Figure 1 that there have been times in the past when hemispheric insolation gradients were generally high (or low) throughout the year. These times are broadly synchronous between the two hemispheres, and a correspondence exists between times with generally high (low) 30-90° insolation gradients throughout the year in the northern hemisphere and times of increasing (decreasing) ice volume - as indicated by the $\delta^{18}O$

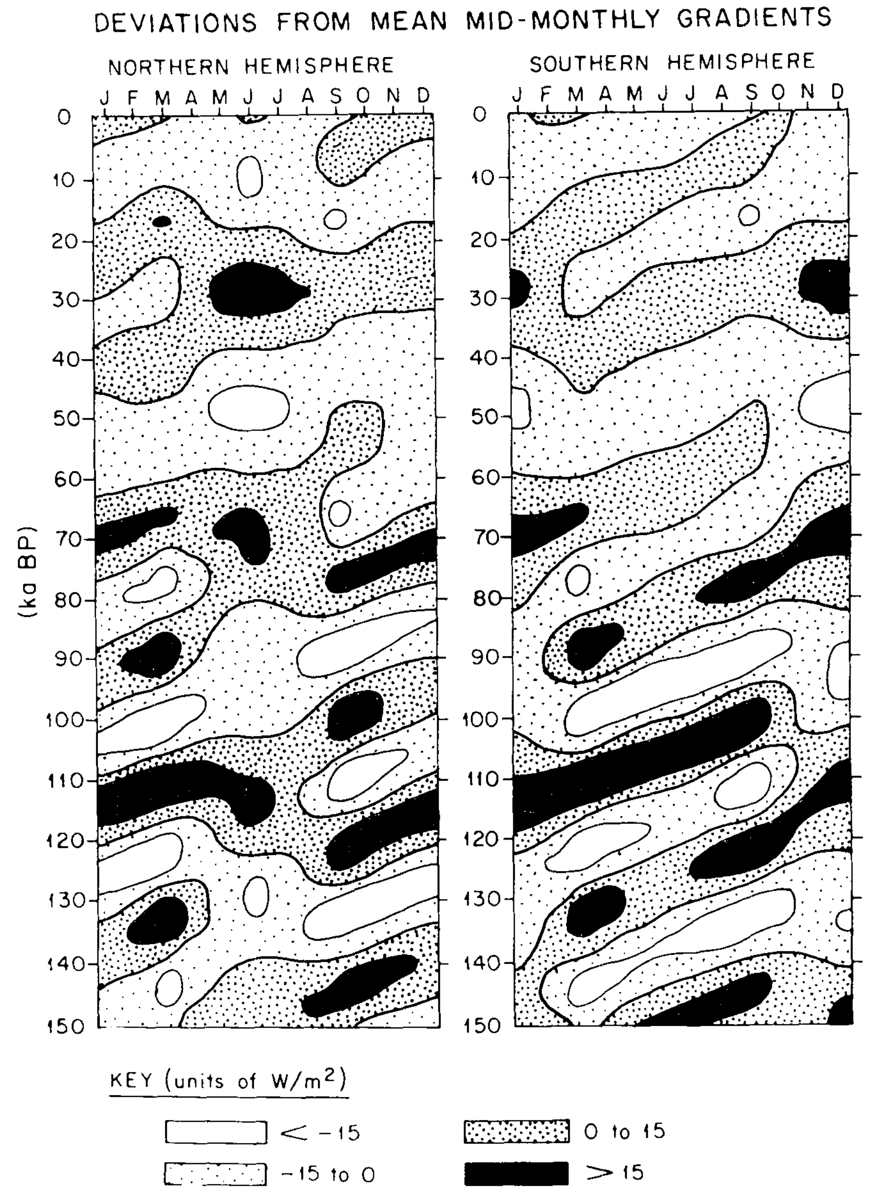

Figure 1 Deviations from monthly 150 kyr mean 30-90° insolation gradients for the Northern (left) and Southern (right) Hemipheres.

record of foraminiferal tests in marine sediments (6). The only dates with positive deviations in at least ten months occur at or near 23, 71, 116, and 141 kyr B.P.. Similarly widespread negative deviations occur at or near 11, 50, 84, and 128 kyr BP.

These relationships are more apparent in Figure 2, which shows the annual sums of the monthly gradient deviations as a function of time. Maxima and minima in the sums occur near the dates identified from Figure 1. Because of the uneven spacing of the mid-monthly values, and because the amplitude of variation of the gradients about the mean is largest during those months when the gradients are strongest, the sums of Figure 2 are weighted sums, with emphasis on the perihelion side of the orbit and on the equinoxes. However, we have produced very similar curves by using the calendar date option and by weighting the mid-monthly values by the amount of time spent in the vicinity of each position.

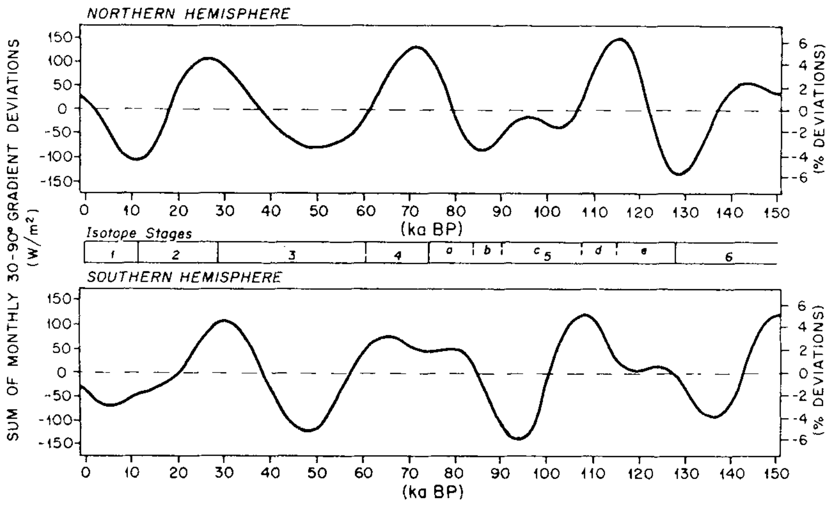

Figure 2 Annual sums of monthly 30-90° insolation gradient deviaions for the Northern (top) and Southern (bottom) Hemispheres. The oxygen isotope stage boundaries of (6) are shown for comparison.

DISCUSSION

A direct correspondence between insolation gradients and the ice volume record is unlikely to reflect accurately a true causal relationship since ice volume changes must certainly lag behind orbitally-induced radiation variations by several thousand years (7). If we assume a lag of about 5000 years, a more sensible correlation is apparent in which interglacials are related to periods of below average integrated annual insolation gradients, and glacials corespond with times of stronger than normal insolation gradients. This lagged correlation is in agreement with the work of Hays, et al. (8) who considered solar radiation receipts at 55-60°N to be the appropriate index of the orbital forcing function. However, energy balance models have often demonstrated that glacierization at these latitudes is not explicable solely in terms of in situ insolation changes (e.g. 9). A more powerful explanation involves both variations in hemispheric insolation gradients and subarctic insolation regimes.

To see how this might work, consider the seasonal pattern of insolation gradient deviations (Figure 3). We note that periods of rapid ice growth (e.g. 23 kyr B.P.) are marked by generally high gradients with maxima in the gradient deviations at the solstices, and follow times of strong autumn insolation gradients by several thousand years (Fig. 1). The correponding insolation regime is one of low summer and high winter receipts. In contrast, times of rapid ice decay (e.g. 11 kyr B.P.) are distinguished by low gradients, with the most negative deviations at the solstices, and are preceded by times of weak autumn insolation gradients. These are times of high summer and low winter insolation.

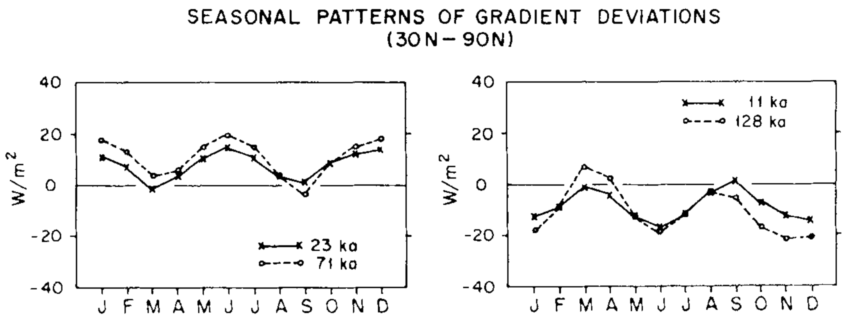

Figure 3 Seasonal patterns of deviations from monthly 150 kyr mean 30-90° insolation gradients at times of selected maxima (left) and minima (right) in the annual sums of figure 2.

If we associate insolation gradients directly with moisture transport to the subarctic, and consider that autumn precipitation is likely to play a particularly important role in glacierization (10), then a coherent picture emerges. Glacial maxima are thus seen to result from increased autumn insolation gradients (higher accumulation, peaking about 10 kyr before the glacial maximum) followed closely by periods of continued above average moisture transport and cool summers. Conversely, interglacials follow decreased autumn insolation gradients (lower accumulation) and subsequent periods of continuous low moisture transport coupled with warm summers (cf. 11). Positive feedback mechanisms within the climate system are also likely to be of considerable importance. For example, ice sheet growth would tend to strengthen hemispheric temperature gradients, reinforcing the insolation gradient changes.

CONCLUDING REMARKS

We have attempted to demonstrate the significance of changes in insolation gradients on climate during the past 150 kyr. Several difficulties remain in establishing such a relationship conclusively. First, the response of the climate system to insolation gradient variations must be more fully understood. Second, the effects of major changes in boundary conditions must be eliminated or corrected for. In this regard, the effects of insolation gradient changes are probably most accurately reflected in the paleoclimatic record when snow and ice cover are minimal, suggesting that the strong shift from very low to very high values of integrated annual insolation gradient, which occured between 125 kyr BP (when boundary conditions were probably similar to today) and 115 kyr BP, would be a good candidate for modelling experiments. Indeed, Royer et al. (12) have used a GCM to model the difference in climte between these dates. Varying only the insolation receipts, not the boundary conditions, they have found a significant zone of moisture surplus and lower temperatures in precisely those areas which are considered to have been important ice growth centers. Further studies along these lines should shed more light on the importance of insolation gradient changes.

REFERENCES

1. Lamb, H.H. : 1972, Climate, Present, Past and Future, vol. 1, Methuen, London.
2. Nicholson, S.E. and Flohn, H. : 1980, Climatic Change, 2, pp. 313-348.
3. Berger, A.L. : 1976, Long Term Variations of Daily and Monthly Insolation during the Last Ice Age. EOS, 57(4), p. 254. Also Progress Report 1976/5, Institute of Astronomy and Geophysics, Catholic University of Louvain, Louvain-la-Neuve, Belgium.
4. Kutzbach, J.E., Bryson, R.E. and Shen, W.C. : 1968, Meteorological Monographs, 8, pp. 134-138.
5. Berger, A. : 1978, J. Atmos. Sci. 35(12), pp. 2362-2367. Also Contribution No 18, Institute of Astronomy and Geophysics, Catholic University of Louvain, Belgium.
6. Shackleton, N.J., and Opdyke, N.D. : 1973, Quaternary Research, 3, pp. 39-55.
7. Barry, R.G., Andrews, J.T. and Mahaffy, M.A. : 1975, Science, 190, pp. 979-981.
8. Hays, J.D., Imbrie, J. and Shackleton, N.J. : 1976, Science, 194, pp. 1121-1132.
9. Williams, L.D. : 1979, Arctic and Alpine Research, 11, pp. 443-456.
10. Kukla, G.J. : 1975, Nature, 253, pp. 600-603.
11. Ruddiman, W.F. and McIntyre, A. : 1981, Science, 212, pp. 617-627.
12. Royer, J.F., Deque, M. and Pestiaux, P. : 1984, in : "Milankovitch and Climate", A. Berger, J. Imbrie, J. Hays, G. Kukla, B. Saltzman (Eds), Reidel Publ. Company, Holland. This volume, p. 733