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SHORT CONTRIBUTION

The zonal and global albedoes of the earth

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ABSTRACT

Changes in global albedo of the Earth can depend on regional variations in reflectivity. We compare here three regional factors that have been considered capable of causing significant changes in global albedo, representing them approximately by zonal averages. Our calculations suggest that

(1) large latitudinal changes in ice cover will have only a slight effect on the planetary albedo, and
(2) latitudinal shifts in the cloud belts can produce significant changes in the planetary albedo.

1. Introduction

The basic balance equation for the effective temperature of the Earth (T_e) can be written in the form

$$\frac{S}{4}(1 - A) = \sigma T_e^4$$

where S is the solar constant; A, the albedo; σ, the Stefan-Boltzmann constant. Over periods of a few years or centuries, changes in S are likely to be small. However, significant variations in albedo may occur on this time-scale, producing corresponding changes in the effective temperature.

The importance of albedo variations as a factor in climatic change has, of course, been discussed in some detail (e.g. Budyko, 1969), but many studies have mainly been concerned with global albedo changes. In particular, many investigations of the effect of cloud changes on the albedo have considered only modifications to the existing global regime (e.g. Schneider, 1972, or Twomey, 1974). Such globally averaged simulations have recently been shown to be inadequate for consideration of certain climatic changes, e.g. the examination of Milankovitch-type fluctuations in climate (Mason, 1976).

We intend to present here a more detailed account of albedo change by going beyond the global albedo to look at possible effects due to zonal variations in reflectivity. Three causative factors for such variations will be considered—namely, changes in (i) surface reflectivity, (ii) cloud cover, (iii) other atmospheric scatterers. Although all three have been discussed in the literature, there has been little systematic, comparative evaluation of their quantitative significance for the zonal albedo. As our interest is in longer-term variations, we shall ignore zonal changes in albedo that have a purely seasonal periodicity, assuming that a zonally averaged value for the albedo can adequately approximate longitudinal variations over many rotations. A number of surface and atmospheric features have, in fact, been shown to be approximately latitude-dependent (e.g. Kukla et al., 1977; Clapp, 1964).

2. Calculation of zonal albedo

The amount of light reflected from any point on Earth depends on two factors—the planar reflectivity of the material concerned and the angle of incidence of the radiation. The spherical albedo for

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the Earth can be calculated by integrating reflected intensity over all points of the Earth's surface, making allowance for variations in reflectivity and angle of incidence at each point. We have constructed semi-empirical curves of reflectivity as a function of angle of incidence for use in these calculations. The initial data for these curves came from various sources (especially Robinson, 1966). The final forms of the curves for different types of surface features are given in Henderson-Sellers (1976). The data available do not allow of high accuracy, but, fortunately, small variations in the relationships concerned do not have a great effect on the final values calculated for the albedo. Since we are interested in annual averages, we have assumed that the rotational axis of the Earth is perpendicular to the incident radiation in estimating zonal reflectivity.

The spherical albedo of the planet was calculated by considering the radiation incident upon, and reflected by, an elemental area of a sphere, dS. The amount of radiation reflected by dS is a function of its reflectivity, $R(\psi)$, where ψ is the angle of incidence of the radiation. It also depends on the foreshortening function, $f(\theta, \phi)$, where θ and ϕ are the spherical angular coordinates of the element dS. The total spherical albedo, A, is given by the ratio of incident to reflected radiation integrated over the sphere. Hence,

$$A = \frac{1}{\pi r^2} \int_{-\pi/2}^{\pi/2} \int_{-\pi/2}^{\pi/2} R(\psi) f(\theta, \phi)\, dS$$

where $f(\theta, \phi) = \cos\theta \cos\phi$; $dS = r^2 \cos\theta\, d\theta\, d\phi$; $\psi = \cos^{-1}(\cos\theta\cos\phi)$.

This double integral was evaluated using a computer program designed to permit the calculation of the albedo of a planet whose surface features could be approximately represented by latitudinal belts.

The computer program initially averages the albedo over the northern and southern hemispheres separately. This allows a comparison with observation, since it is possible to derive from observational data the two hemispheric albedoes averaged over a year. The use of a hemispheric albedo also provides an indication of what differences can arise between the hemispheres due to zonal averaging. The computer program finally derives a global albedo. This makes it possible to evaluate the overall effect on the albedo of specific zonal variations.

3. Results

We have first calculated a "standard" model that should provide a reasonable approximation to the present global albedo of the Earth. We have assumed that the land areas are concentrated between approximately latitudes 40°–77° in the northern hemisphere and 0°–19° in the southern hemisphere (in reasonable agreement with data from Sellers, 1965). There is a 50% cloud cover distributed symmetrically north and south in equatorial and mid-latitude zones. The ice caps extend polewards of ±60° latitude. This model produces a global albedo of 30.2%, which is close to the currently accepted value (Vonder Haar and Suomi, 1971), though there remains some doubt about the exact figure.

We next examine what effect altering the zonal values of surface reflectivity can have. It is frequently supposed that alterations in the extent of the polar caps must have the greatest influence on albedo. However, we find that changing the lower latitude limit for caps by ±20° makes very little difference to the global albedo (Table 1). Indeed, as can be seen from the data in the table, replacing ice by snow as the main surface material, whilst retaining the present latitude limits, has an appreciably greater effect on the albedo than altering the extent of the polar caps.

The influence of changes in the zonal cloud distribution on the albedo is a good deal more important. As would be expected, an increase in the total cloud cover (e.g. from 50% to 60%) produces a major change in the global albedo. More interestingly, relatively small changes in the positions of the cloud belts can also produce significant differences. Table 1 indicates the effect of symmetrical displacements of the mid-latitude cloud belts by 5° (i) equatorwards, (ii) polewards. The observational data on hemispherical albedoes suggest, however, that the albedo is about the same for the two hemispheres. The final series of calculations was therefore designed to produce a model that fitted this requirement. Hemispheric albedoes were equalized by slightly perturbing the cloud cover distribution in each hemisphere, whilst retaining a global average value of 50%. The best fit is indicated in Table 1: it shows that a small asymmetry in cloud cover can readily satisfy the observational requirements. This result is particularly interesting since the north–south asym-

Table 1. *The albedo for different imposed constraints*

	Global albedo	Northern hemisphere albedo	Southern hemisphere albedo	Percentage change in albedo
Imposed Constraint				
1. Standard (NH land 40°–77°) (SH land 0°–19°) Symmetric 50% cloud cover	30.2	29.6	30.7	0
2. Snow *not* ice > 60°	30.5	30.0	31.0	+1.0
3. Ice > 80° only	30.0	29.5	30.6	−0.7
4. Ice > 40°	30.2	29.6	30.7	0
5. Mid-latitude cloud belt: symmetric move 5° poleward	29.6	29.0	30.1	−2.0
6. Mid-latitude cloud belt: symmetric move 5° equatorward	31.1	30.6	31.6	+3.0
7. 60% cloud	34.9	34.5	35.3	+15.6
8. Attempt to equalize hemispheric albedoes by cloud cover alteration global cover = 50% N.H. cover = 49% S.H. cover = 51%	30.2	30.1	30.2	0

metry in land/ocean distribution implies that such hemispheric differences in cloud albedo may well occur (Henderson-Sellers, 1978).

The effect of a dust veil is difficult to calculate, since it depends on a number of factors, including the particle size distribution and the rate of injection of material. However, a rough estimate based on conditions corresponding to those following the Krakatoa eruption in 1883 suggests that volcanic dust veils should not introduce a change of more than 0.5% in the hemispheric albedo.

4. Discussion

These calculations suggest two conclusions.

(i) Small latitudinal changes in cloud cover are more likely to produce significant variations in the global albedo than are larger latitudinal changes in the extent of the polar caps, or in the occurrence of dust veils. Hence, in determining climatic effects due to albedo change, the latter two agents should normally be considered only after cloud cover variations have been eliminated.

(ii) Latitudinal changes of the magnitude suggested in our cloud cover calculations are certainly feasible. Changes of this order in the latitudinal pattern of the westerlies seem to have occurred in historic times (Lamb and Johnson, 1966; Winstanley, 1973). This implies, in turn, that significant fluctuations in the global albedo of the Earth, due to zonal changes in cloud cover, must have taken place. The feedback effect of such fluctuations clearly needs to be taken into account in any detailed modelling of climatic change.

REFERENCES

Budyko, M. I. 1969. The effect of solar radiation variations on the climate of the earth. *Tellus 21*, 611–619.

Clapp, P. G. 1964. Global cloud cover for seasons using Tiros nephanalysis. *Mon. Weath. Rev. 92*, 495–507.

Henderson-Sellers, A. 1976. A theoretical study of the evolution of the atmospheres and surface temperatures of the terrestrial planets, Ph.D. thesis, University of Leicester.

Henderson-Sellers, A. 1978. Surface type and its effect upon cloud cover: a climatological investigation. *J. Geophys. Res. 83*, 5057–5062.

Kukla, G. J., Angell, J. K., Korshover, J., Dronmia, H., Hoshiai, M., Namias, J., Rodewald, M., Yamamato, R. and Iwashima, T. 1977. New data on climatic trends. *Nature 270*, 573–580.

Lamb, H. H. and Johnson, A. I. 1966. Secular variations of the atmospheric circulation since 1750. *Geophys. Mem. 110.* London: H.M.S.O.

Mason, B. J. 1976. Towards the understanding and prediction of climatic variations. *Q. J. Roy. Met. Soc. 102*, 473–499.

Robinson, N. 1966. *Solar radiation.* Elsevier.

Schneider, S. H. 1972. Cloudiness as a global feedback mechanism: the effects on the radiation balance and surface temperature of variations in cloudiness. *J. Atmos. Sci. 29*, 1413–1422.

Sellers, W. D. 1965. *Physical climatology*, p. 5. University of Chicago Press.

Twomey, S. 1974. Pollution and the planetary albedo. *Atmos. Envir. 8*, 1251–1256.

Vonder Haar, T. H. and Suomi, V. E. 1971. Measurements of the earth's radiation budget from satellites during a five year period. Part 1: extended time and space means. *J. Atmos. Sci. 28*, 305–314.

Winstanley, D. 1973. Rainfall patterns and general atmospheric circulation. *Nature 245*, 190–194.