

other global nephelyses⁸ also tend to have greater cloud cover in the SH (see figure). That the latitudinal cloud amounts differ rather considerably from one another in the figure is not surprising when it is recognized that the USAF three-dimensional nephelyses is predominantly a satellite archive for 1979 whereas the Berlyand *et al.* data are predominantly surface-based and accumulated over a much longer period. In any case, it is well known that evaluations of latitudinally averaged values of total cloud amount differ by at least $\pm 10\%$ (absolute cloud amount)⁹. Thus if Schwartz had chosen to use a different source for his F_c values, the $\alpha_c F_c$ curves in his Fig. 1 would have been modified. Moreover, these curves are highly suspect as they represent the planetary albedo as viewed from the top of the atmosphere in areas designated, from another incompatible data source, to be cloudy.

We conclude that the hypothesis of Charlson *et al.* has not been refuted.

A. HENDERSON-SELLERS

School of Earth Sciences,
Macquarie University,
New South Wales 2109, Australia

K. MCGUFFIE

Department of Applied Physics,
University of Technology,
Sydney, PO Box 123, Broadway,
New South Wales 2007, Australia

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STR—Claiming that man-made emissions of SO_2 have had no effect on surface-temperature trends or planetary albedo, Schwartz' attempts to refute our hypothesis² of a biological mechanism for climate regulation. His arguments are flawed for several reasons.

First, although Schwartz interprets the analyses of Jones *et al.*^{3–5} to show that the changes in surface temperature in the past century for the Southern Hemisphere (SH) is not significantly greater than that for the Northern Hemisphere (NH), Jones *et al.* have themselves also said⁶, "the warmth of the 1980s is most evident in the Southern Hemisphere". That statement refers to a single decade only, but an independent analysis⁷ has extended it back through two more decades and concluded that the 20-year trend of surface air temperature (1958–77) over the oceans has a latitudinal dependence, with the SH warming more rapidly.

We do not know why different analyses of the historical record of surface temperatures lead to opposite conclusions about the trends. But even if those studies were to be reconciled they might still not offer a clear test of the effect of sulphate aerosol on cloud albedo, because there are probably climate factors other than cloud albedo that could cause the temperature trends to differ in the two hemispheres. (See also Wigley⁸.)

Using a published cloud climatology and published measurements of planetary albedo, Schwartz also concludes that average cloud albedo is no greater in the NH than in the SH. He takes this as evidence against an influence of industrial sulphur pollution on cloud albedo, despite the fact that the lifetime of sulphur in the atmosphere is typically not more than a few days, so the effect of pollution-derived aerosol may not extend much beyond the NH continents. Therefore it is likely that the geographical footprint of the pollution aerosol does not greatly overlap that of the sensitive marine stratus clouds, particularly in the subtropics.

However, sulphate aerosols, whether derived from industrial pollution or from dimethylsulphide, can be expected to influence only one of the determinants of cloud albedo, namely the effective cloud-droplet radius, r_{eff} . As Stephens⁹, for example, has shown, cloud albedo is a function principally of three variables: vertically integrated liquid water content (liquid water path, LWP), solar zenith angle, and r_{eff} . It is unlikely that the average LWP of clouds in the SH is the same as in the NH. As the average LWP for each hemisphere is unknown, the effect of sulphur on r_{eff} cannot be inferred just by comparing hemispheric-average albedos, as Slingo¹⁰ emphasized. Long-term trends in planetary albedo are also not available, even though they have been measured for three decades, because of changes in the satellite instruments.

Much of Schwartz's argument is based on a comparison of non-sea-salt sulphate (n.s.s. SO_4^{2-}) concentration over the oceans in the Northern and Southern hemispheres. He compares measurements made by a variety of authors with a variety of techniques. Unfortunately, there is considerable uncertainty about the accuracy of such measurements. Very few sampler intercomparisons have been made, none of them conforming to the rigorous standards that are now expected to be part of intercomparison protocols. Often the large size fraction ($>1\text{--}2\ \mu\text{m}$, depending on the size cut of the sampler), which typically contains about 30–40 per cent of n.s.s. SO_4^{2-} , is either not collected or its n.s.s. SO_4^{2-} content is ignored. Samples of fine n.s.s. SO_4^{2-} and total n.s.s. SO_4^{2-} should therefore not be compared, as has been done by Schwartz².

If we take the data in Schwartz's Table 1

at face value, we see that it contains data from both 'dusty' and 'clean' episodes in the North Pacific and North Atlantic. Much of the sulphate in the dust episodes is actually on coarse particles and therefore provides few cloud condensation nuclei (CCN). During the 'low-dust' season, Barbados shows about the same values as Samoa, and the summer Arctic and North Sea trajectory data from Velen are about the same as Cape Grim and Punta Arenas. We conclude that many of the NH sites are about as clean as the climatically and biogeographically comparable SH sites for much of the time. The only significant difference arises during dust transport events (where much of the SO_4^{2-} is coarse and does not provide many CCN) or at some obviously and expectedly polluted sites — for example, Bermuda. Much of the dust transport is of course natural, and would not contribute to a potential time trend. It seems that anthropogenic inputs are significant for boundary-layer n.s.s. SO_4^{2-} levels only over the Atlantic north of 30°N , and possibly over the northern North Pacific, but sulphate distributions there are presently not well known. Looking at our own cruise data from the tropical Pacific, we find that the NH n.s.s. SO_4^{2-} data¹¹ are actually lower than the SH and equatorial ones. Consequently, 40 per cent at most of the area over the NH oceans might experience significantly elevated CCN concentrations.

The aircraft data from the North Pacific off Washington State and the south Indian Ocean off Tasmania do suggest significant differences in n.s.s. SO_4^{2-} levels^{12,13}. But the total aerosol sulphur in the atmosphere is comprised of sulphate and methanesulphonic acid. Thus, when methanesulphonic acid is added to n.s.s. SO_4^{2-} , the total aerosol sulphur in the sub-cloud mixed layer is essentially the same for the Tasmania and Washington data sets. We know that the size distributions of methanesulphonic acid and n.s.s. SO_4^{2-} are similar, and we may assume that they are internally mixed, and that both contribute to the mass of soluble particles, and thus to CCN active at low supersaturation. But in the free troposphere there is a pronounced difference between the two ▶

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data sets, with levels over the North Pacific substantially elevated relative to the south Indian Ocean. It is not clear, however, just how far two experiments of only about two-weeks duration each can be extrapolated, and how much the aerosol at these altitudes contributes to cloud formation.

Finally, we note that Schwartz² did not attempt to test the hypothesis that most natural marine CCN are produced from dimethylsulphide. Regardless of any climate role of CCN, understanding their sources, properties, distribution and variability are important objectives.

ROBERT J. CHARLSON

Department of Atmospheric Sciences,
University of Washington,
Seattle, Washington 98195, USA

JAMES E. LOVELOCK

Coombe Mill Experimental Station,
Launceston, Cornwall PL15 9RY, UK

MEINRAT O. ANDREAE

Max-Planck-Institut für Chemie,
Postfach 3060, D-6400 Mainz, FRG

STEPHEN G. WARREN

Glaciology Section,
Earth Sciences School,
University of Melbourne,
Parkville, Victoria 3052, Australia

SIR—Schwartz¹ proposes that because aerosol sulphate concentrations are considerably higher in the industrialized Northern Hemisphere (NH) than in the Southern Hemisphere (SH), the climatic effect should be observed in the difference between the hemispheric temperature trends. Based on data presented by Jones *et al.*^{2,4}, he reports that there is no difference in the temperature trends of the two hemispheres over about the past century and therefore no supporting evidence for the role of SO₂ in climate.

We do not think that such a conclusion is justified given the sparsity of temperature data, particularly for the SH, earlier this century. A recent analysis of the spatial patterns in temperature trends for 1947–86 in the NH and in the SH (data for the Antarctic were not available until the late 1950s) points to almost uniform warming in the SH and large regions of both cooling and warming trends in the NH⁵. Earlier studies also indicate regions of positive and negative temperature anomalies in the NH^{6–8}. Given the large geographic variability of sulphate concentrations, one could expect its impact to be regional. Among the areas which exhibit cooling are eastern North America and Europe, both known to be regions of exceptionally high SO₂ emissions that have increased substantially over the past century. Large regions of cooling are also observed over the North Atlantic and North Pacific oceans⁵. Qualitatively, the

observations are not inconsistent with the idea of regional compensation of CO₂ warming by aerosols. Therefore, given the complexity of the climate system, the question of the influence of sulphates on climate remains open.

JOYCE GAVIN

GEORGE KUKLA

Lamont–Doherty Geological Observatory,
Columbia University,
Palisades, New York 10964, USA

THOMAS KARL

National Climatic Data Center,
Asheville, North Carolina 28801, USA

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SIR—For a link to exist between changes in gaseous sulphur emissions and changes in planetary albedo several conditions must be met. The conditions associated with air masses containing anthropogenic SO₂ emissions may not be conducive to changing cloud albedos. First, increases in concentrations of cloud condensation nuclei (CCN) must necessarily lead to increases in typical cloud-drop concentrations and decreases in drop size. Such an assumption is consistent with observation when CCN concentrations are low — as expected over cleaner areas in both the Northern hemisphere (NH) and the Southern Hemisphere (SH). But in areas where the CCN concentration exceeds 1,000 cm⁻³ and where sulphate concentrations exceed 2,000 ng cm⁻³, this relationship is not observed². Such a lack of correlation is expected because as CCN concentrations increase, supersaturation levels in clouds become depressed, causing a smaller fraction of aerosol particles to act as CCN³. Because continental air masses typically contain plenty of CCN, addition of anthropogenic sulphur is not expected to affect the cloud-drop number density in these air masses.

Second, the measurements of sulphate concentration given by Schwartz¹ are in terms of total mass per unit volume; no measurements for number density of sulphate particles are provided. Schwartz assumes that sulphate concentrations would be proportional to CCN concentrations and that the increased sulphate concentrations observed in the NH would imply increased numbers of CCN. This would only be expected if the conversion of anthropogenic SO₂ to sulphate were dominated by gas-phase processes followed by homogenous nucleation of SO₄²⁻ to the

aerosol. In fact, a significant proportion of SO₂ is converted to sulphate via aqueous reactions which take place in cloud drops. These reactions would increase the size of existing aerosol and CCN particles but not their number. An increase in size is observed in air masses which originate over continents and move offshore⁴.

Satellite observations presented by Schwartz¹ indicate that the cloud component of the planetary albedo is larger in the SH than in the NH, which he says is opposite to the difference expected if sulphate controls the number of cloud droplets. However, he implicitly assumes that the cloud fraction is the same for each hemisphere, which is not the case. The fractional cloudiness of the SH is generally larger than that of the NH², so that the cloud albedos are not necessarily greater in the SH. An additional shortcoming is the lack of distinction between marine and continental clouds, whose albedos are influenced by the difference between the albedos of the underlying surface. Moreover, the liquid water content of clouds varies widely with latitude and altitude. If satellite measurements of planetary albedo are to be used to evaluate the influence of sulphate aerosols on cloud albedo, comparisons between marine clouds of comparable liquid-water content must be performed.

Finally, the observed albedos of optically thick clouds are significantly lower than expected from a straightforward theoretical analysis. One explanation for the discrepancy is the absorption by graphitic carbon particles that have been scavenged by the cloud drops⁶. This requires the carbon to be at the surface of the drop in order to substantially increase its absorption, but this has been observed in laboratory experiments⁷. The carbon, of course, is associated with urban pollution and would originate in the same continental regions as the anthropogenic sulphur discussed by Schwartz¹. For clouds of intermediate optical depth the effect of carbon on cloud albedo is much less significant, but the lowered albedo of optically thick clouds would still tend to obscure the analysis by Schwartz because he does not distinguish between optically thick and thinner clouds.

STEVEN J. GHAN

JOYCE E. PENNER

KARL E. TAYLOR

Lawrence Livermore National Laboratory,
PO Box 808, L-262,
Livermore, California 94550, USA

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