

Are global cloud albedo and climate controlled by marine phytoplankton?

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The recent suggestion that dimethylsulphide emissions by marine phytoplankton control global albedo and mean temperature would also imply a strong climatic influence of man-made SO₂. Anthropogenic SO₂ emissions exceed marine emissions of dimethylsulphide globally and are confined largely to the Northern Hemisphere. But no such influence of SO₂ emissions is found either in the present cloud component of planetary albedo or in 100-year temperature records.

RECENTLY, Charlson, Lovelock, Andreae and Warren¹ (hereinafter CLAW) proposed that production of dimethylsulphide (DMS) by marine microorganisms is the major source of aerosol sulphate in the remote marine atmosphere and, in turn, of cloud condensation nuclei (CCN). They suggest that this process, by influencing planetary albedo, comprises a component of a biological mechanism for climate regulation. Specifically, it is hypothesized that an increase in marine DMS emissions would increase the number density of aerosol sulphate particles and, in turn, the number density of cloud droplets, thus enhancing cloud albedo. This enhancement would reduce global temperature generally, including ocean temperatures, and would consequently reduce marine productivity and DMS emission; that is to say, the process is a negative feedback system for control of the Earth's temperature. Such a feedback system was subsequently and independently suggested by Mészáros².

Here I examine the hypothesized link between gaseous precursors of aerosol sulphate, and global albedo and mean temperature. Because marine DMS emissions are substantially lower than present emissions of other gaseous precursors of atmospheric sulphate (principally SO₂ associated with fossil fuel combustion) globally and especially in the Northern Hemisphere, then consequently, if, as CLAW suggest, marine DMS emissions exert a major influence on global mean albedo and temperature, such an influence should also result from anthropogenic SO₂ emissions. The potential for such anthropogenic influence on cloud albedo and global mean temperature has been noted previously^{3,4}. But CLAW explicitly "ignore the perturbations of the atmospheric sulphur cycle by man-made fluxes of SO₂... and... consider only the natural fluxes, which currently represent about 50% of the total flux of gaseous sulphur to the atmosphere, and which still dominate the atmospheric sulphur cycle in the Southern Hemisphere". I argue here that the increase in SO₂ emissions over the past 100 years and the contrast in

gaseous sulphur emissions between the Northern Hemisphere (NH) and Southern Hemisphere (SH) constitute a global experiment that tests the hypothesis of ref. 1, that planetary albedo and mean temperature are regulated by marine DMS emissions.

It will be seen that a comparison of the present NH and SH cloud component of planetary albedo and of 100-year temperature records yields no indication of any influence of anthropogenic SO₂ emissions that is either qualitatively or quantitatively consistent with the expectations in this respect based on the CLAW hypothesis.

Emission rates

Emissions of reduced sulphur compounds and of sulphur dioxide have been critically reviewed recently⁵⁻⁷ and are summarized in Table 1. Andreae⁶ estimates total global biogenic emissions of sulphur gases to be 95 ± 30 Tg of sulphur per year, DMS and H₂S each accounting for about half of this total (43 ± 20 and 32 ± 27 Tg S yr⁻¹, respectively). The estimate⁶ for marine DMS emissions, 40 ± 20 Tg S yr⁻¹, is based on concentrations of DMS in ocean surface water at a variety of locations together with estimates of sea-air exchange rates. A lower DMS emission rate of 16 Tg S yr⁻¹ (uncertain to a factor of two) is given by Bates *et al.*⁸. Natural emission rates in Table 1 are consistent with budget estimates based on considerations of turnover times and of concentrations of sulphur compounds in the atmosphere⁹.

On a global basis, SO₂ emissions are roughly equal to biogenic emissions and are at least twice as great as marine DMS emissions. A *prima facie* case exists, therefore, that anthropogenic sulphur emissions cannot be neglected in examining the possible influence of biogenic gaseous sulphur compounds on global cloud albedo and climate. Also, as anthropogenic SO₂ emissions have increased to their present level almost entirely within the last 100 years (ref. 5 and H. Rodhe, private communication cited in ref. 7), any climatic influence of these emissions should be discernible in records over this period¹⁰. Furthermore, the asymmetric distribution of anthropogenic SO₂ emissions over the globe suggests that the influence of gaseous sulphur emissions on climate may also be tested by interhemispheric comparisons, significant interhemispheric transport (on a timescale of one to two years) being precluded by the short atmospheric residence times of these substances^{9,11}.

Distribution of aerosol sulphate

For sulphate derived from anthropogenic SO₂ to serve as a surrogate to test the CLAW hypothesis, this material must be widespread throughout the NH. The geographical distribution of sulphate attributable to anthropogenic emissions of SO₂ is examined in Table 2, which presents concentrations of aerosol sulphate in boundary-layer air at locations remote from

Table 1 Gaseous sulphur emission rates

Emission source	Northern Hemisphere	Southern Hemisphere	Global
Marine DMS	17	23	40
Total marine biogenic	22	28	50
Terrestrial biogenic	32	16	48
Total biogenic	54	44	98
Anthropogenic SO ₂	98	6	104
Total	150	50	200

Data are from Cullis and Hirschler⁵, except for marine DMS (Andreae⁶), apportioned according to ocean surface area: 42% NH and 58% SH. Emission rates are in units of Tg S yr⁻¹.

Table 2 Measured concentration of sulphate (or sulphur) aerosol at remote locations in the Northern and Southern Hemisphere

Location	Sulphate concentration* (ng S m ⁻³)	Comments	Ref.
Northern Hemisphere			
<i>High-latitude sites</i>			
Alert, Mould Bay, Igloolik; Canadian Arctic (66–83° N)	(200–1,000) (20–70)	NSS SO ₄ ²⁻ ; 1-week samples; 3- to 4-year data record Winter–Spring Summer	15
Faeroe Islands (62° N)	1,100 (700–1,400) 140 (30–230)	NSS SO ₄ ²⁻ British trajectory (~1,000 km); 4 1-day samples Atlantic trajectory; 4 1-day samples	13
Velen, Sweden (58° N)	960 [1.4] 60 [2.2]	Sub-μm S; 1-day samples British trajectory (~1,000 km); 12 samples North Sea trajectory (Northwest air); 14 samples	18
<i>Atlantic and Caribbean</i>			
Western North Atlantic (33–38° N, 65–70° W)	800 ± 500	Sub-μm S; 26 8- to 68-hour samples	18
Bermuda (32° N)	530 [3.0]	Sub-μm S; 10 2- to 4-day samples	18
Bermuda	1,300 630 390 330	Sub-2.5-μm NSS SO ₄ ²⁻ ; 39 1-day samples Northeast US trajectory (~1,200 km) Southeast US trajectory (~1,100–1,500 km) Caribbean trajectory Southeast trajectory	14
Barbados (13° N, 60° W)	650 ± 230 300 ± 190 120 ± 65 250 ± 180	All NSS SO ₄ ²⁻ ; 1-day samples 'High dust'—Europe or Africa trajectory 'Low dust' All	17
<i>Pacific</i>			
Eastern Pacific Ocean off Washington State (47–48° N)	140 ± 60 80 ± 30	Aircraft sampling, boundary layer; 3 flights; Pacific trajectories; May Total NSS SO ₄ ²⁻ Sub-1.5-μm NSS SO ₄ ²⁻	20
Midway Island (28° N)	260 ± 90 100 ± 30 190 ± 260	NSS SO ₄ ²⁻ ; 1-week samples; onshore flow only 'Dusty'; 29 samples 'Clean'; 27 samples All; 56 samples	16
Oahu (21° N)	160 ± 130 90 ± 80 120 ± 110	NSS SO ₄ ²⁻ ; 1-week samples; onshore flow only 'Dusty'; 24 samples 'Clean'; 32 samples All; 56 samples	16
Guam (17° N)	150 ± 240	NSS SO ₄ ²⁻ ; 1-week samples; onshore flow only; 49 samples	16
Belau (7° N)	210 ± 190	NSS SO ₄ ²⁻ ; 1-week samples; onshore flow only; 40 samples	16
Fanning Island (4° N)	210 ± 50	NSS SO ₄ ²⁻ ; 1-week samples; onshore flow only; 48 samples	16
Southern Hemisphere			
Samoa (14° S)	60 [2.4]	Sub-μm S; 17 3- to 5-day samples	18
Samoa	130 ± 50	NSS SO ₄ ²⁻ ; 42 1-week samples	19
New Caledonia (22° S)	170 ± 130	NSS SO ₄ ²⁻ ; 46 1-week samples	19
Norfolk Island (29° S)	110 ± 50	NSS SO ₄ ²⁻ ; 41 1-week samples	19
Cape Grim, Tasmania (41° S)	90 ± 20	NSS SO ₄ ²⁻ ; multi-year data record under 'baseline' conditions	43
Tasmania, off West Coast	(22–70)	NSS SO ₄ ²⁻ ; aircraft sampling, boundary layer; 8 flights; ocean trajectories; Austral summer	21
Punta Arenas, Chile (54° S)	52 [0.3] 83 11	Austral summer; sub-μm S; 9 3- to 5-day samples Austral summer; NSS S; 140 4-hour samples Austral winter; sub-μm S; 1 5-day sample	18
South Pole	76 ± 24 29 ± 10	Austral summer; total S; sea salt small; 40 several-day samples Austral winter; total S; sea salt 4–10%; 49 several-day samples	44

* Mean ± standard deviation or geometric mean [geometric standard deviation] or (range).

† NSS SO₄²⁻: Non-seasalt sulphate.

industrial activity. Such locations are pertinent because aerosol sulphate concentrations are obviously high in industrialized regions and at locations immediately influenced by transport from these regions. By comparison, median 24-hour boundary-layer sulphate concentrations at non-urban locations of the north-eastern United States are ~2,000 ng S m⁻³ (ref. 12). Total aerosol samples are corrected for sea salt by reference to Na or Mg; this correction is generally unimportant for measurements

of only sub-micrometre (sub-μm) sulphate (that fraction arising from gas-to-particle conversion, which is of concern here). The data in Table 2 represent measurements by numerous investigators using a variety of techniques and protocols for widely differing sampling periods, so that any comparison of data from different investigators must be made with caution. Nonetheless, Table 2 indicates a pattern in which aerosol sulphate concentrations at remote NH locations substantially exceed those at

remote SH locations. Concentrations in the NH are mostly greater than $\sim 150 \text{ ng S m}^{-3}$, often much greater, whereas concentrations at remote locations in the SH are almost invariably less. Concentrations in the NH also exhibit substantially greater variability than those in the SH, indicating the intermittent presence, in the former case, of aerosol sulphate transported from distant regions.

For several NH sites, high concentrations have explicitly been ascribed to long-range transport from continental regions or, more specifically, from regions of industrial activity, by the trajectory of the air arriving at the site or by the presence of other air constituents. For example, high sulphate concentrations at the Faeroe Islands are attributed to transport from the United Kingdom, 1,000 km distant¹³, and high sulphate concentrations at Bermuda are attributed to transport from North America (1,100 km)¹⁴. The marked seasonality of sulphate concentrations in the Canadian Arctic¹⁵ is attributed to transport from Eurasian sources during late winter and spring; this seasonal cycle is exhibited also by a number of other anthropogenic constituents. High non-seasalt (NSS) sulphate at several North Pacific islands commonly coincides with soil dust, transported mostly from Asia¹⁶. Similarly, high NSS sulphate at Barbados, coincident with high incidence of soil dust, is attributed to transport from North Africa or Europe (distances of 5,000 km or more)¹⁷.

Several data sets in Table 2 afford direct comparison of measurements at NH and SH locations. Lawson and Winchester¹⁸ present measurements of sub- $\mu\text{m S}$ for which NH concentrations were an order of magnitude greater than SH concentrations. Prospero *et al.*¹⁶ and Saltzman *et al.*¹⁹ present an extensive set of measurements from several North Pacific¹⁶ and South Pacific¹⁹ islands; the mean NSS sulphate concentration for five NH islands was 30% greater than that for three SH islands.

Andreae *et al.*²⁰ and Berresheim *et al.*²¹ report aircraft measurements of NSS sulphate by similar techniques in boundary-layer air off the coast of Washington state²⁰ and off the west coast of Tasmania²¹, both sets of data relating to air behind cold fronts moving over open ocean without contact with land for several days. The NSS sulphate concentrations for Washington state ranged from 90 to 190 ng S m^{-3} , whereas those for Tasmania ranged from 20 to 70 ng S m^{-3} . NSS sulphate concentrations in the free troposphere at Tasmania (30–60 ng S m^{-3} at STP) were comparable to those in the boundary layer, but those at Washington state were substantially greater (150–270 ng S m^{-3} at STP). This situation argues strongly against a marine source. Indeed, Andreae *et al.*²⁰ suggest, in the case of the Washington state measurements, that the sulphur cycle in the free troposphere was dominated by transport from Asia.

Sulphate in precipitation

Table 3 presents volume-weighted mean concentrations of NSS sulphate obtained in long-term records of wet-only event sampling at several remote NH and SH sites²². The measurements indicate markedly greater concentrations in the NH, supporting the present assertion that sulphate derived from anthropogenic emissions exerts an influence on air composition throughout the NH.

Long-range transport of anthropogenic sulphur is indicated also by the dependence of the composition of precipitation on back trajectory. For samples collected in the eastern North Atlantic, Nyberg²³ found that for trajectories from North America (4,000–5,000 km), NSS SO_4^{2-} concentrations were 12–37 $\mu\text{eq l}^{-1}$, whereas for a trajectory emanating from the Azores, concentrations were $\sim 6 \mu\text{eq l}^{-1}$. Similarly, Jickells *et al.*²⁴ established that, in precipitation at Bermuda, systematically greater acidity was associated with trajectories from North America (mean H^+ concentration = 41 $\mu\text{eq l}^{-1}$) than with trajectories from the Caribbean (8 $\mu\text{eq l}^{-1}$) or the east (12 $\mu\text{eq l}^{-1}$); one can assume that the dependence of NSS SO_4^{2-} concentration on

trajectory was similar, because H^+ and NSS SO_4^{2-} were highly correlated (correlation coefficient $R = 0.94$; slope = 0.94).

Recently, Whelpdale *et al.*²⁵ concluded that even the most remote parts of the North Atlantic are undoubtedly affected by anthropogenic pollution and that only a few data are available in which precipitation is derived from air from 'clean' regions. Their estimate of sulphate concentrations in 'background' marine precipitation samples (6–8 $\mu\text{eq l}^{-1}$) substantially exceeds concentrations reported from remote SH sites (Table 3), indicat-

Table 3 Volume-weighted mean concentrations of non-seasalt sulphate in precipitation of remote sites

Location	NSS SO_4^{2-} $\mu\text{eq l}^{-1}$	Dates	Ref.
Poker Flat, Alaska (67° N)	10.2	5/80–5/81	22
Bermuda (32° N)	18.2	5/80–5/81	45
	13.9	8/82–5/84	46
San Carlos, Venezuela (2° N)	3.0	9/80–3/81	22
Katherine, Australia (14° S)	3.2	1980–1984	47
Amsterdam Island (38° S)	5.0	5/80–8/83	47
Torres del Paine, Chile (47° S)	2.1	1984–1985	47

ing that even this background contains a substantial component of anthropogenically derived sulphate. Considerably higher concentrations were reported for samples obtained with trajectories from North America or Europe.

Sulphate in polar ice

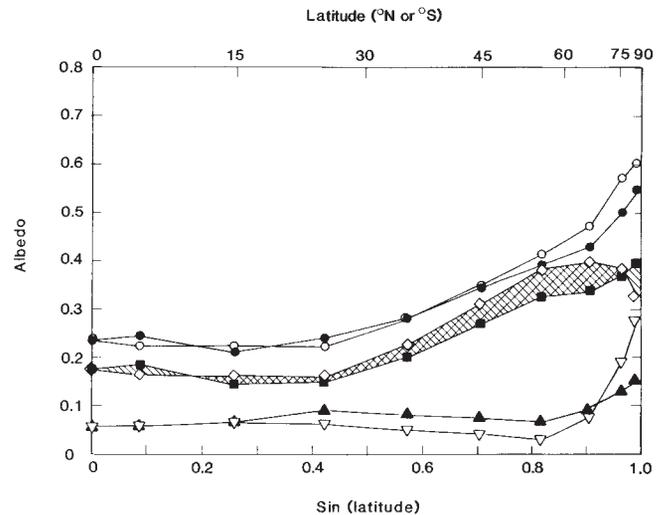
Substantial increases in sulphate concentrations over the past century have been noted in polar ice at NH sites. Concentration of NSS SO_4^{2-} in ice at Dye 3 Station, Greenland (65° N) has tripled since ~ 1900 ^{26,27}. Similarly, there has been a substantial increase in conductivity of melt water from core samples obtained at Ellesmere Island (81° N) from 1910 to 1980, which is attributed to increased deposition of sulphate, nitrate and associated cations²⁸. In contrast, a corresponding increase in sulphate concentration is not observed in ice cores obtained at Antarctica^{29,30}. One may conclude that deposition of NSS SO_4^{2-} at these remote NH sites has increased as a consequence of anthropogenic emissions and that the relative increase in this deposition is comparable to that in NH sulphur emissions.

Thus, comparisons of concentrations of NSS sulphate in aerosol, precipitation and ice cores at remote locations in the NH and SH establish that there are substantially greater concentrations throughout the NH than in remote SH locations, mainly as a result of anthropogenic emissions. These observations confirm my premise that if marine DMS emissions were to exert a control over global cloud albedo and mean temperature, then there should be an influence on these variables from anthropogenic SO_2 emissions.

Interhemispheric comparison of cloud albedo

A key component of the CLAW hypothesis is that the cloud contribution to planetary albedo should increase with increasing emissions of sulphate precursors. In the absence of measurements that would permit comparison of present and pre-industrial albedos, I seek to identify the effect of anthropogenic sulphur emissions on planetary albedo by a comparison of the present albedos of the two hemispheres. The expected magnitude of the interhemispheric albedo difference may be determined from the example given in ref. 1, which indicates that a 30% increase in CCN concentration would increase planetary albedo above marine clouds by 0.016, and average global albedo by 0.005, where the latter quantity takes into account the fraction of the Earth's surface covered by marine clouds. Following this example, and using a NH:SH CCN ratio of 3:1 (compare Table 1), I obtain a difference between average NH and SH albedos

Fig. 1 Average annual zonal mean over 10° latitude bands for Northern and Southern Hemispheres of total planetary albedo α_T and of cloud and clear-sky components, $F_C\alpha_C$ and $(1-F_C)\alpha_S$, respectively. The key is as follows: ●, total albedo (NH); ○, total albedo (SH); ■, Cloud component (NH); ◇, cloud component (SH); ▲, clear-sky component (NH); ▽, clear-sky component (SH). Single-hatching indicates that the NH cloud component exceeds the SH component; cross-hatching indicates the reverse. Equal distances on the lower abscissa correspond to equal areas on the Earth's surface.



of 0.023. Essentially the same result is obtained using the logarithmic dependence of albedo on CCN concentration proposed by Twomey *et al.*⁴. Although such an albedo difference is undoubtedly an overestimate, in view of the non-uniform distribution of sulphate concentrations in the NH, even a 50% difference in CCN concentrations between the two hemispheres (see Tables 2 and 3) would, in the absence of other factors, lead to an expected mean interhemispheric albedo difference of 0.008 (NH greater than SH).

In view of differences in land area and surface features of the two hemispheres (and resultant differences in surface albedo) I have looked for indication of an influence of NH SO₂ emissions by comparing not the total albedo of each hemisphere but the component of this albedo that is due to clouds, under the assumption that this quantity was more nearly comparable in the pre-industrial atmosphere. The cloud component of albedo is a direct measure of the contribution of clouds to solar radiative forcing of the Earth's heat budget³¹ and is thus an appropriate indicator of a possible influence of gaseous sulphur emissions on this budget.

Figure 1 shows, for each hemisphere, the annual-average mean of total albedo and of the cloud and clear-sky components of this albedo, over 10° latitudinal zones. The cloud component is evaluated³¹ as

$$F_C\alpha_C = \alpha_T - (1 - F_C)\alpha_S$$

where F_C represents average fractional cloud coverage³², α_C represents average cloud albedo, and α_T and α_S represent measured³³ average total and clear-sky albedo, respectively. There is no indication that the cloud component is systematically greater in the NH than in the SH; if anything, the reverse is true throughout the latitude range 15–75°, which range encompasses the bulk of the industrialized regions of the NH. These data thus give no evidence of the enhancement of the cloud component of mean NH albedo that would be expected if NH SO₂ emissions were to influence the Earth's heat budget and temperature in a manner consistent with the CLAW hypothesis.

Changes in temperature

A second test for the influence of anthropogenic SO₂ on climate is provided by examining temperature records for changes in global mean temperature or for hemispherical asymmetries. The example given by CLAW indicates that the hypothesized increase in mean global albedo of 0.005 associated with a 30% increase in CCN concentration results in a change in global average solar radiative heating, ΔQ , of -1.7 W m^{-2} . The resul-

tant equilibrium decrease in mean global temperature is $\Delta T = \Delta Q/\lambda$, where λ , the climate sensitivity parameter, is estimated³⁴ to be $1.8 \text{ W m}^{-2} \text{ K}^{-1}$ (uncertain to a factor of two); this yields $\Delta T = -1.0 \text{ K}$. (This value of ΔT , and others evaluated here, are all uncertain to a factor of two because of uncertainty in λ . Evidently CLAW used a somewhat lower value of λ , yielding $\Delta T = -1.3 \text{ K}$.) Analogously, an increase of 0.023 in mean NH albedo (which, according to the CLAW hypothesis, would result from a tripling of NH sulphur emissions) should give rise to a decrease in mean NH temperature of 4.4 K if, along with the increase in emissions and concentrations, the cooling effect were confined entirely to the NH^{35,36}. Alternatively, if the temperature change were distributed over both hemispheres, an average global temperature decrease of 2.2 K would be indicated. Again, because of spatial non-uniformities in CCN concentration, such temperature changes may be overestimates. But even a NH albedo increase of 0.008, which corresponds in the CLAW hypothesis to a uniform 50% increase in CCN concentration over pre-industrial values, would result in a NH temperature decrease of 1.5 K in the absence of interhemispheric coupling, or a global temperature decrease of 0.8 K if the cooling was distributed globally.

These estimates represent equilibrium temperature changes, whereas any currently observable temperature decrease corresponding to the indicated change in radiative forcing would be less, by a factor of about two, because of the lag time in reaching thermal equilibrium^{10,39}. It should be noted that such predicted temperature change is comparable to, and of opposite sign to, the change in global temperature that would be expected from increased concentrations of CO₂ and other 'greenhouse' gases^{10,34,37}. I return to this point later.

Several analyses of temperature records in the Northern and Southern Hemispheres over the past hundred years have recently been presented. Jones *et al.*³⁸⁻⁴⁰, by examining records for land and sea-surface temperatures in the two hemispheres, present evidence for warming trends that are essentially identical in both hemispheres. The land temperatures record (1881–1984) indicates warming rates (K per century) of 0.51 (NH) and 0.47 (SH). The corresponding warming rates determined from the sea surface temperature record (1904–1984) are 0.60 (NH) and 0.57 (SH). Hansen and Lebedeff³¹ propose a global warming trend of $0.6 \pm 0.1 \text{ K per century}$, again with no discernible interhemispheric difference. Thus there is no cooling trend in either hemisphere, or any lesser warming in the NH relative to the SH, as a consequence of the increase in sulphur emissions in the NH over this time period, of magnitude such as would be expected according to the CLAW hypothesis.

Summary and discussion

The hypothesis that emissions of DMS by marine phytoplankton exert a regulatory influence on mean global cloud albedo and temperature has been tested by searching for a possible influence of anthropogenic SO₂ emissions on these properties. These emissions exceed estimated global marine DMS emission by a factor of two, are comparable to total biogenic gaseous sulphur emissions globally, are confined largely to the NH, and have reached their present levels within the past 100 years. Moreover, aerosol sulphate is widespread throughout the NH at concentrations well in excess of those in remote SH locations. These features of anthropogenic SO₂ emissions and resultant sulphate concentrations suggest that the influences of anthropogenic SO₂ emissions on mean hemispheric cloud albedo and on mean hemispheric or global temperature would be evident if these aspects of global climate were controlled by sulphate derived from marine DMS emissions. The absence of any excess mid-latitude cloud component of albedo in the NH relative to the SH, and the lack of any global cooling or of any reduced warming in the NH relative to the SH, indicate that these variables are not controlled by anthropogenic sulphates, and by extension, are not controlled by marine DMS emissions.

The apparent lack of observable influence of emissions of gaseous sulphur compounds on climate is puzzling. There is little doubt that SO₂ and reduced sulphur compounds are precursors to aerosol sulphate⁴². It is also well established that sulphate-containing aerosol particles are effective cloud condensation nuclei^{1,3}. There is also persuasive theoretical^{1,3,4} and observational³ evidence that the albedo of liquid-water clouds increases with cloud droplet number density. It thus seems reasonable that an influence on the cloud contribution to global mean albedo and temperature might be expected, as Twomey *et al.*⁴, CLAW¹ and Mészáros² have suggested. The observational evidence, however, suggests otherwise. Thus, unless there is a countervailing influence upon global or hemispheric cloud albedo or temperature that has masked the influence of SO₂ emissions, it seems unlikely that global cloud albedo and temperature are controlled by emissions of gaseous sulphur compounds.

One such influence that must be addressed is that of warming caused by CO₂ and other greenhouse gases. Current evaluations^{34,37} of expected global temperature changes since 1850 resulting from increased concentrations of CO₂ and other infrared-active gases (CH₄, N₂O, chlorofluoromethanes) indicate an expected mean temperature increase of ~1 K. (This temperature change is evaluated from modelled radiative forcing^{34,37} with the same sensitivity parameter λ employed above and exhibits the same factor of two uncertainty.) Such an expected temperature increase is comparable to but somewhat larger than estimates of actual temperature changes³⁸⁻⁴¹, the difference being attributed^{10,37} both to the time lag in response of global temperature to the change in radiative forcing and to the uncertainty in λ , although in principle some of that difference might be due to enhanced cloud albedo from anthropogenic sulphate. The several greenhouse gases are, however, all long-lived relative to interhemispheric mixing time, and are hence uniformly mixed globally, leading to an essentially symmetric forcing function on temperature, whereas anthropogenic sulphate, confined largely to the NH, would exert its influence largely in that region. The lack of hemispherical asymmetry in the rate of change in global temperature³⁸⁻⁴¹ thus suggests that compensation of cooling from enhanced cloud albedo by warming caused by greenhouse gases does not account for the observations. Also, greenhouse heating would not account for the lack of enhanced cloud contribution to NH albedo.

In conclusion, it would seem that the lack of discernible response of mean global or hemispheric albedo or temperature to anthropogenic SO₂ emissions indicates that control of these properties is too complex to be governed by a single variable of this type. Nonetheless, the potential for a substantial human influence on global climate by the mechanism examined here makes it mandatory to gain a thorough understanding of the processes that control cloud albedo and its influence on global climate.

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