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Climate: The Influence of Aerosols

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McCormick and Ludwig (1967) presented arguments to show that a buildup of atmospheric aerosols could have the effect of increasing the albedo, thereby cooling the earth. Bryson (1968) has further discussed this possibility. This point of speculation seems particularly important since pollution of the whole atmosphere by this finely divided particulate matter is strongly suggested. The analogous case of global CO_2 increase seems to be accepted, suggesting that effects of this scale are not unexpected. Unfortunately, the analysis of the albedo variation depends very strongly on several unknown variables, i.e., the size distribution of the particles and their scattering and absorption cross sections. Scattering can be thought of as being associated with the previously mentioned effect of cooling while absorption would lead to heating. It is possible to estimate the relative effect of light scattering and absorption by the following analysis.

Consider the atmosphere to be a flat, nearly transparent, thin, uniform scattering and absorbing layer above the earth's surface. The incoming radiation from the sun in the zenith is presumed to be affected by aerosols while outgoing radiation is not. The amount of energy absorbed, W, in unit time by the earth-atmosphere system is the sum of the absorption at the surface and by the atmosphere, i.e.,

$$W = W_{\mathrm{sfc}} + W_{\mathrm{atm}}.$$

This can be expanded in terms of the intensity of light incident on the system, and the properties of both the atmosphere and surface. Using the Beer-Lambert law for a simple description of light passing through the atmosphere,

$$\frac{S_{fs}+S_t}{S_0} = \exp[-(b_{abs}+b_{bs})x],$$

where S_{fs} denotes forward scattered light, S_t the transmitted (unabsorbed) light, S_0 the initial intensity of incoming radiation, x the atmospheric thickness, and b_{abs} and b_{bs} the extinction coefficients due to absorption and backscatter, respectively. Assuming no directional effects at the surface, the incoming energy can be written as

$$\begin{aligned} W &= A(S_{fs}+S_t)+S_0[1-\exp(-b_{abs}x)], \\ &= \underbrace{AS_0\exp[-(b_{abs}+b_{bs})x]}_{\text{Surface heating}} + \underbrace{S_0 - S_0\exp(-b_{abs}x)}_{\text{Atmospheric heating}}, \end{aligned}$$

where A is the fractional absorption of the surface.

Thus, the basic effect of a backscattering, nonabsorbing aerosol would clearly be to decrease W, thereby cooling the earth-atmosphere system. The effects of b_{abs}, however, are twofold:

1) Since $A<1$, any increase in b_{abs} results in an increase in W for a given b_{bs}.

2) The location of heating is removed from the surface to higher in the atmosphere, resulting in increased static stability as well as increased W.

The effect of a secular increase in aerosols, then, might be either an increase or a decrease in W depending on the relative magnitudes of b_{abs} and b_{bs}, and the absolute magnitude of b_{abs}. It is possible to estimate relative values for b_{abs} and b_{bs} in order to determine which dominates.

Examination of scattering-angle diagrams for atmospheric aerosols, for instance those of Bullrich (1964), suggests that the backscattering component of extinction is perhaps 10% of the total extinction coefficient due to scattering. Other data (Waldram, 1945) show a comparable magnitude for the light absorption by industrial haze in the visible spectrum. Therefore, the net climatological effect of industrial smoke, which does contain light absorbing substances such as carbon and iron oxide, could well be to heat and not to cool the earth.

It seems important to seek better information concerning the relative magnitude of the backscattering and absorption coefficients in addition to the current measurement of total attenuation (McCormick and Ludwig, 1967). In particular, the importance of specific industrial pollutants such as carbon and the iron oxides should be determined. Naturally occurring light absorbing material such as volcanic dust should also be investigated to ascertain the relative importance of the human factor.

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Reply

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While we disagree with his conclusions, we feel that the approach taken by Schneider is a useful one, particularly since it uses nomenclature more common to the atmospheric sciences than those used by Charlson and Pilat (1969). The concept of albedo is perhaps more clearly understood than the light extinction coefficient, although the two are clearly related. In checking the model proposed by Schneider, the differences with ours are "second order" in character. Schneider includes the effects of multiple light reflections from the surface which we (and others) have neglected (Atwater, 1970; Mitchell, 1971), giving rise to terms that do not appear in simpler models. We consider this difference inconsequential in view of the other gross assumptions involved (e.g., the neglect of directional effects or of the assumption of a single, very low albedo for the whole earth).

Our main objection relates to the values chosen to represent the albedo. Table 1 (Schneider) suggests that the earth is decidedly black with an albedo of 0.1 ± 0.05, which is certainly very unrealistic for the whole earth including clouds. Had Schneider used higher values of either surface albedo or of the ratio α/α_{BS} (which are realistic), heating would have been shown to be possible. At $\alpha_S=0.1$, α/α_{BS} must be about 4 to yield heating, while if $\alpha_S=0.3$ (typical of deserts), $\alpha/\alpha_{BS}\approx1$ produces heating. This result is quantitatively similar to our earlier estimates (Charlson and Pilat, 1969). While $\alpha_S=0.1$ might be appropriate for open ocean, it is not valid for the whole earth. A global value for the earth/

atmosphere system (including clouds) of $\alpha_S \approx 0.3$ seems more reasonable while some kinds of surface have still higher albedos (e.g., snow, ice).

If perchance Schneider wishes to limit his consideration to the low albedo surface and lower tropospheric aerosol below clouds, then the model may not be appropriate due to the complex, diffuse illumination below the clouds. In any event, Mitchell (1971) shows that it is imperative to consider latent as well as sensible heat, and that even for low albedo surfaces ($\alpha_S \approx 0.1$) heating by aerosol is possible if the surface is moist (e.g., oceans, vegetation).

Ensor *et al.* (1971) show that the critical ratio of aerosol absorption coefficient to backscatter coefficient to balance heating and cooling, $(b_{abs}/b_{bs})_{\text{critical}}$, depends on both the nature of the radiative balance model and the terrestrial albedo. Both the simple model of Charlson and Pilat and the more complex model of Mitchell yielded (b_{abs}/b_{bs}) critical ratios in the approximate range from 0.1 to 10, depending on the albedo and other assumptions of the models. However, it is especially important to point out that the effect of the complex part of the refractive index has an inordinately strong effect on the b_{abs}/b_{bs} ratio such that a complex part of 0.01 is sufficient in most cases to cause heating rather than cooling *regardless* of the model used, and for all albedos >0.2.

We concur that the question "whether the combined aerosol-surface albedo is comparable to or greater than the surface albedo alone" is important. However, it should be clear that the effective albedo may be governed in large part by the relative magnitudes of aerosol absorption and backscatter.

Since the microphysical properties of absorption and backscatter have not been measured for terrestrial aerosols in background situations, it is not possible to state categorically that either heating *or* cooling would result from a secular increase in the atmospheric aerosol. However, it seems clearly possible, as we originally stated, that heating of the earth/atmosphere system could occur.

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