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POLLUTION AND THE PLANETARY ALBEDO

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Abstract—Addition of cloud nuclei by pollution can lead to an increase in the solar radiation reflected by clouds. The reflection of solar energy by clouds already may have been increased by the addition of man-made cloud nuclei. The albedo of a cloud is proportional to optical thickness for thin clouds, but changes more slowly with increasing thickness. The optical thickness is increased when the number of cloud nuclei is increased. Although the changes are small, the long-term effect on climate can be profound.

INTRODUCTION

The planetary albedo is simply the fraction of incident light from the sun which is reflected back into space by the earth. The light not reflected is absorbed by the atmosphere and by the surface and provides the energy input for driving the motions of atmosphere and ocean, maintaining the climate, and, in short, making the earth habitable. If the planetary albedo were unity, the earth would be brighter than it is now but would just be a dead, cold, white speck in space, orbiting the sun but unable to share the sun's energy.

The eminent Russian climatologist Budyko (1969) suggested that a reduction of perhaps as little as 2 per cent in the solar radiation falling on this planet could cause an irreversible "flip" from our present apparently stable and more or less pleasant climate to another stable but not so pleasant state in which the earth, much whiter and much colder, would be in the grip of another ice age. It would seem that an increase in the planetary albedo, if not accompanied by some compensating effect, would be equally harmful.

Attention has lately been directed to the effect of pollution on a global scale on the energy balance of the earth, but most of this attention has been confined to effects outside clouds where particles reflect and absorb radiation and thereby modify the planetary albedo. The purpose of this paper is to point out that a direct connection exists between pollution and the number of drops in a cloud and hence an influence on the optical thickness and reflectance of the clouds (cloud albedo). There have been suggestions that pollution can lead to "dirty" clouds with lower albedo, but the volume of water cycled through the atmosphere is so much greater than that of any pollutant that is is difficult to see how such effects could be significant unless there were a magnifying influence by which (say) a particle absorbed very much more efficiently when immersed in a cloud drop. The order of multiple scatterings which occur in clouds do effectively lengthen the photon path lengths, but shorter path lengths are also provided when the incident light is oblique and a detailed analysis shows that the globally averaged absorption by particles is not enhanced by mixing the absorbing particles into an optically thick scattering layer. There is to date no mechanism known to the writer whereby the formation of clouds magnifies the particulate absorption.

The effect which will be discussed here is quite different: it is suggested that pollution gives rise to whiter (not darker) clouds—by increasing the droplet concentrations and thereby the optical thickness of clouds.

CLOUD ALBEDO

The planetary albedo is a sum of reflection by clouds, ground surfaces, ocean surfaces, atmospheric gases, and atmospheric particles, but of these the clouds contribute by far the most to the total reflection, which brings us to the question of cloud albedo, i.e. the fraction of incident light reflected (diffusely) by clouds; this diffuse reflection, in turn, is caused by a multitude of individual scattering events, in which light experiences a change in direction after an encounter with a single drop or ice particle within the cloud.

The light scattered by a single drop changes in intensity with direction, exhibiting in its scattering diagram marked maxima and minima, the positions of which depend on the wavelength. Most of the light scattered by a cloud is scattered not just once but successively by as many as 20, 30 or more drops, so that a photon emerging upward from the top of a cloud will have travelled a meandering path since it entered the cloud; the light emerging in a particular direction is made up of many photons which have arrived there by many different routes. Consequently, the scattered light from a cloud varies only slowly with angle. A further consequence is that the amount of light emerging from the top and base of a cloud does not depend critically on details of the cloud's microphysics and scattering properties or their spatial variation, but only on bulk-averaged quantities. Of these, the optical thickness is by far the most important. Optical thickness is most easily defined by stating that, when a unit incident vertical beam of light passes through a layer of optical thickness τ, a fraction $e^{-\tau}$ emerges unscattered; the remaining $1 - e^{-\tau}$ has been scattered one or more times in passing through the layer. This energy is not necessarily dissipated; it may just be redistributed. The second quantity relevant to cloud scattering is the single-scattering albedo $\bar{\omega}$—the fraction of scattered energy which appears in some other direction, i.e. the fraction *not* absorbed in a single-scattering event. For water and visible light, absorption is slight, so that all or most of the energy removed by a scattering is conserved and $\bar{\omega}$ can be taken to be unity. The third quantity to be looked at is the asymmetry factor $\overline{\cos\theta}$: This is merely the power-averaged value of the cosine of the scattering angle. Most of the energy scattered by cloud drops is scattered forward, so $\overline{\cos\theta}$ is positive and fairly close to one, say 0·8–0·9.

Given the optical thickness τ of a cloud layer, the single-scattering albedo and the asymmetry factor, we can compute quite precisely, for any direction of illumination (i.e. solar elevation), how much of the incident radiation will emerge in any direction upward (reflected) or downward (transmitted). A particularly important quantity is the overall "cloud albedo." This is not at all the same as the single-scattering albedo, which is a measure of how well energy is conserved in a single-scattering event; the cloud albedo is the fraction of the incident light energy which is reflected upward by the cloud and which, therefore, does not penetrate to the earth's surface or to the atmosphere below the cloud.

A glance at Fig. 1 shows the dominant role of optical thickness in determining the cloud albedo. Once τ is greater than about 5 or 6, virtually all the light has been scattered at least once. (Less than 1 per cent of normally incident light gets through without being scattered.) But the figure shows that redistribution of the scattered energy, how much goes up and how much goes down, continues to change appreciably out to $\tau = 10, 20, 30$ and

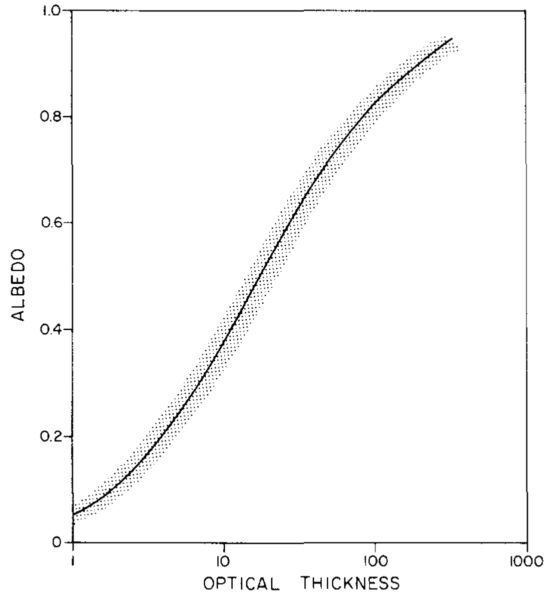

Fig. 1. Cloud albedo vs optical thickness. Dotted area indicates extent of variation about the median due to variations in $\overline{\cos\theta}$ (which is determined primarily by drop size).

beyond. To an observer on the ground, these latter would be all thick clouds, in the sense that the sun's disc could not be seen through them.

OPTICAL THICKNESS OF CLOUDS

The geometric thickness of a cloud and the amount of water condensed out in a unit area column through the cloud are determined by large-scale atmospheric motions, water vapor content, etc. and can in no direct way be affected by pollution. But the optical thickness involves the size of the cloud drops—in fact, to a good approximation, the optical thickness is twice the sum of the cross-sectional area of all drops in the column—and, as we shall see, the numbers and sizes of the drops can be affected by pollution, more specifically by the particles in the air in which the cloud formed. All aerosol particles act as centers for condensation at some relative humidity, but in clouds the humidity rarely exceeds 101 per cent, and only the more efficient particles are activated. The greater the number of such particles, the greater the number of cloud drops—the proportionality is not a direct one because increased numbers tend to lower the maximum relative humidity which is attained; this partly offsets the increase in number, leading to a dependence of a cloud-drop number on roughly the 0·8 power of the particle numbers. That such particles are produced in urban–industrial pollution is certain; it is less certain that, on a global scale, urban–industrial pollution is a significant contribution to the total number.

CLOUD NUCLEI AND INDUSTRIAL POLLUTION

Figure 2 shows the measured concentration of "cloud nuclei"—particles promoting condensation at a slight r.h. excess above 100 per cent (in this instance, at 100.75 per cent)—at a monitoring station near the south-eastern coast of Australia. The wind change caused

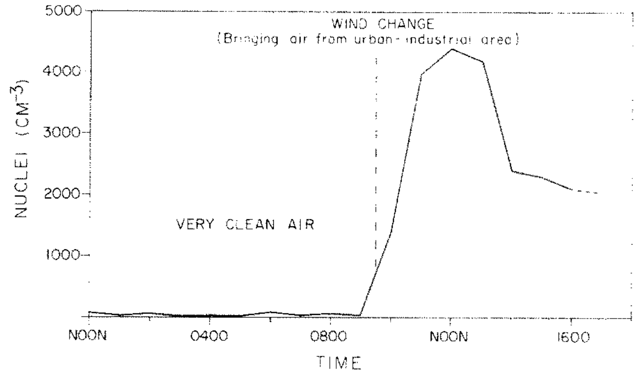

Fig. 2. An example of the effect of an incursion of polluted air on cloud nucleus concentrations.

by a sea breeze replaced generally westerly air (from the land, but relatively clean) by northeasterly marine air from the Pacific, which, en route to the station, passed across the Wollongong–Port Kembla industrial area. This area (population about 200000; annual fuel consumption estimated at 3×10^6 tons) produces a considerable part of Australia's steel and is a compact and well-defined region containing also coal mines, a large power station and other smaller industries. The effect of the urban-industrial pollution on the cloud-nucleating particles is obvious. Aircraft measurements of the concentrations of these particles indicate that the Wollongong–Port Kembla area puts out more than 10^{16} cloud nuclei s^{-1}. The whole global atmosphere contains some 10^{26}–10^{27} such nuclei, and their average life-time is a few days; this implies a global production rate of 10^{21}–10^{22} s^{-1}. It would, therefore, take at least 30000 Wollongong–Port Kemblas to match the global production. The world's population is almost 20000 times that of Wollongong–Port Kembla, but it is hardly realistic to make a projection of the global scale on the basis of population; fuel or energy consumption would seem a better basis, and if we make an estimate of global output on that basis, we conclude that about 3×10^{19}—or about 3 per cent—of the global production of nuclei is artificial. As the world's consumption rate increases, so presumably will the artificial-nucleus component of the atmospheric aerosols.

The conclusion from all this is that reflection of solar energy by clouds may have already been increased by the addition of man-made pollution, and this can be expected to increase further as time goes on. The relationships outlined earlier imply that a 10 per cent increase in nuclei would lead to about a 2.5 per cent increase in optical thickness. The cloud albedo is proportional to optical thickness for thin clouds, but changes more slowly with increasing cloud thickness. If we take 0.5 as a typical cloud albedo, it will increase by about 1 per cent (i.e. to 0.505) if the optical thickness increases 2.5 per cent. These changes are small, but in the light of Budyko's estimate that a 2 per cent reduction in the earth's input of solar energy would produce a catastrophic change in climate, such changes can hardly be regarded as insignificant.

It is worth noting that an increase in cloud reflectance, i.e. the brightness of the clouds, is not at all equivalent to an increase in cloud cover. Both lead to an increase in the planetary albedo, but the former does not change the balance of infrared radiation to any appreciable extent, since clouds are believed to be black over most of the infrared. Increased cloud cover, on the other hand, replaces a relatively warm radiating surface by a colder cloud surface, decreasing the outgoing longwave radiation and so counteracting the effects at short wavelengths.

SIZES OF CLOUD NUCLEI

It is also instructive to look at the amounts of material involved. Measurements of the sizes of natural cloud nuclei have pointed to a radius typically a little larger than one millionth of a centimeter. The mass of such a particle would be around 10^{-17}–10^{-16} g. A number of independent estimates of the global production rate have been made by workers in the field. These have shown surprisingly close agreement around a figure of 10^{21} cloud nuclei per second. (This is only a small fraction of the total number of particles of every kind; many particles are not capable of nucleating condensation at a very slight r.h. excess over 100 per cent.) The turnover of cloud nuclei at its present level, therefore, involves something like 10^4–10^5 g or 10–100 kg s^{-1}, not at all a large amount of material. Converted to an annual rate, it represents about 4×10^5–4×10^6 tons y^{-1} (e.g. 0.4–4 Mtons y^{-1}). The annual global consumption of coal and of fuel oil runs into thousands of Mtons y^{-1}, while estimates of sulfate formation, ammonium salt formation, and nitrate production in the atmosphere all have resulted in figures of tens to hundreds of Mtons y^{-1}; the National Air Pollution Control Administration (1970), in its inventory of air pollutant emissions for 1968, assessed hydrocarbon emission to be 29 Mtons y^{-1}. The possibility that cloud albedo can be affected by man's activities cannot therefore be discounted simply on the grounds of the amounts of material involved. The present level of emission is already volumetrically much greater than what is involved in cloud nucleus production; if a sizable fraction of this emission had happened to be in the form of cloud nuclei, it seems quite certain that cloud–drop concentrations and thereby cloud albedo would have been profoundly affected.

CONCLUSIONS

The relationships discussed are each individually well-established. The dominant role of cloud reflectance in determining the planetary albedo is well-recognized and documented; London and Sasamori (1971), for example, cite an albedo of 15 per cent for a cloud-free earth, compared to a 50 per cent albedo for an earth totally overcast with clouds similar to those presently occurring in the cloud-covered portions. The present value of the planetary albedo, a little more than 30 per cent, lies about midway between these extremes. The relationship between cloud albedo and optical thickness follows directly from classical radiative transport theory; the relative insensitivity of cloud albedo to $\overline{\cos\theta}$ and its almost complete insensitivity to higher moments of the scattering diagram (phase function) are well known and especially clarified by the work of van de Hulst *et al.*, on multiple scattering in thick layers (e.g. van de Hulst and Grossman, 1968).

The relationship between cloud nuclei and cloud–drop concentration (which inevitably affects optical thickness) has been confirmed experimentally (Squires and Twomey, 1960; Twomey and Warner, 1967). The ability of pollution to produce effective nuclei has been noted by many investigators in different places (Wieland, 1956, Switzerland; Squires, 1966, Denver; Hobbs, Radke and Schumway, 1970, Eastern Washington; Fitzgerald and Spyers-Duran, 1973, St Louis, to name but a few).

Even though there are several links in the connection, the relationship between increased cloud albedo and pollution seems well founded (although direct experimental verification of the effect would obviously be desirable). Only the magnitude of the effect is uncertain, the greatest uncertainty being in the estimation of global nucleus production rates from relatively few measurements of production rates for individual urban-industrial centers. Pollution also increases both scattering and absorption in cloud-free air by introducing additional aerosol particles, an aspect which has been discussed by a number of investigators (e.g. SMIC, 1971), but these effects are of quite a different character. The probable importance of the influence of pollution on the cloud reflectance lies in the fact that the process of cloud condensation causes some of the particles in the atmosphere to grow into cloud droplets which will have cross-sectional areas typically a hundred thousand times that of the nucleating particles. There is, in this way, a great magnification of the light scattering power of those particles. The effect which has been discussed here is indirect in nature, but it intervenes in the reflection of solar radiation by the naturally occurring clouds, which is the dominant contributor to reflection by the planet earth, the reflecting power being supplied by the 500 million Mtons of water exchanged yearly between the oceans and the atmosphere.

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