Reports

Effect of Ship-Stack Effluents on Cloud Reflectivity

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Under stable meteorological conditions the effect of ship-stack exhaust on overlying clouds was detected in daytime satellite images as an enhancement in cloud reflectivity at 3.7 micrometers. The exhaust is a source of cloud-condensation nuclei that increases the number of cloud droplets while reducing droplet size. This reduction in droplet size causes the reflectivity at 3.7 micrometers to be greater than the levels for nearby noncontaminated clouds of similar physical characteristics. The increase in droplet number causes the reflectivity at 0.63 micrometer to be significantly higher for the contaminated clouds despite the likelihood that the exhaust is a source of particles that absorb at visible wavelengths. The effect of aerosols on cloud reflectivity is expected to have a larger influence on the earth's albedo than that due to the direct scattering and absorption of sunlight by the aerosols alone.

THE EFFECT OF MAN-MADE AEROSOLS on climate has received considerable attention (*1*), especially on how aerosols scatter and absorb solar radiation and thereby influence the amount of radiation reflected by the earth-atmosphere system and absorbed at the earth's surface (*2*). Little attention, however, has been focused on how aerosols might influence the radiative properties of clouds and thus have an additional influence on the radiation budget. It has been estimated that if the increase in man-made aerosols is taken to be proportional to that for carbon dioxide, the effect of the aerosols on the earth's radiation budget through the interaction with clouds would be comparable in magnitude but opposite in sign to that of increased carbon dioxide (*3*). Algae in seawater may be a source of sulfate aerosol, which in turn affects the reflectivity of maritime clouds and thereby exerts a biological control on the radiation budget and climate (*4*).

The effect of aerosols on the earth's radiation budget through their influence on clouds may be several times that of the direct interaction of the aerosol with solar radiation. Aerosols are a source of nuclei around which cloud droplets and ice crystals form. These nuclei, which may be only a few hundredths of a micrometer in radius upon entering a cloud with suitable supersaturation, can rapidly form cloud droplets that are typically several micrometers in radius (*5*). Although the nuclei interact only weakly with solar and terrestrial radiation because of their small size, the cloud droplets that they form interact strongly with the radiation field. Thus ships at sea have been observed to generate cloud lines in regions where the concentrations of naturally occurring aerosol and cloud condensation nuclei are evidently too low to form clouds (*6*). Although such cloud lines are readily observed in visible-light satellite imagery data, the aerosol contribution to reflected sunlight is difficult to detect and quantify (*7*).

Theoretical studies and observations indicate that as the cloud condensation nuclei in stratiform water clouds increase in number, the size of the droplets decreases and the number of droplets increases (*8*). The increase in droplet concentration, the decrease in droplet size, and possibly the added absorptivity due to the presence of the condensation nuclei themselves are reasons for expecting the radiative properties of polluted clouds to differ from those of nonpolluted clouds. We studied the change in reflectivity of low-level stratus and stratocumulus clouds that were contaminated by the exhausts of ships at sea. As shown in Fig. 1, the contaminated clouds are clearly evident as "ship tracks" in data from the National Oceanic and Atmospheric Administration's NOAA-9 Advanced Very High Resolution Radiometer (AVHRR) at 3.7 μm and at a resolution of 1 km by 1 km. These tracks are not so apparent in images at either 0.63 or 11 μm. In several cases, we identified the ships causing the tracks by using satellite navigation to obtain the apparent latitudes, longitudes, and times for the sources and then compared these with ship positions that are part of routinely logged maritime weather reports.

Ship tracks are infrequently found in the imagery data. The lengths of those found so far indicate that they are detectable only when stagnant conditions persist for extended periods of time. Under normal conditions, mixing disperses the pollution over broad scales and the typical variability in cloud radiative properties masks the effects due to contamination. A random selection of ten orbital passes that contain cases of extensive stratus and stratocumulus conditions off the coast of California yielded only two with ship tracks. Single-layered stratus conditions at the 250 km by 250 km scale typify 25 to 40% of the observations for the Pacific Ocean (*9*). This frequency, coupled with our experience with the ten orbital passes, leads us to believe that ship tracks may occur in only 5 to 10% of all orbital passes.

To compare the reflectivities of contaminated clouds to those of similar noncontaminated clouds, regions 500 km by 500 km that contained ship tracks (Fig. 1) were first divided into 60 km by 60 km mesoscale

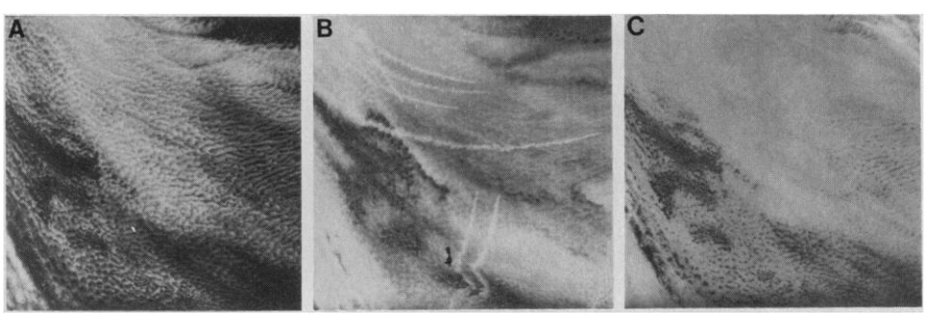

Fig. 1. Images constructed from 1 km by 1 km NOAA-9 AVHRR data: (**A**) 0.63-μm reflectivity, (**B**) 3.7-μm radiance, and (**C**) 11-μm radiance for a 500 km by 500 km region of ocean off the coast of California. In the images at 0.63 and 11 μm clouds are light objects that stand out against the dark, cloud-free ocean background. In the 3.7-μm image this separation is not possible because thermal emission from the cloud-free ocean in some cases rivals the reflection and emission by clouds. The data were taken at 2246 U.T. on 3 April 1985. The ship tracks evident at 3.7 μm are due to a shift toward smaller droplets for the contaminated clouds. The shift causes an increase in reflected sunlight at 3.7 μm. It has no influence on emission at 11 μm, and the small increase in 0.63-μm reflectivity is masked by the large variability in reflectivity typical for such clouds.

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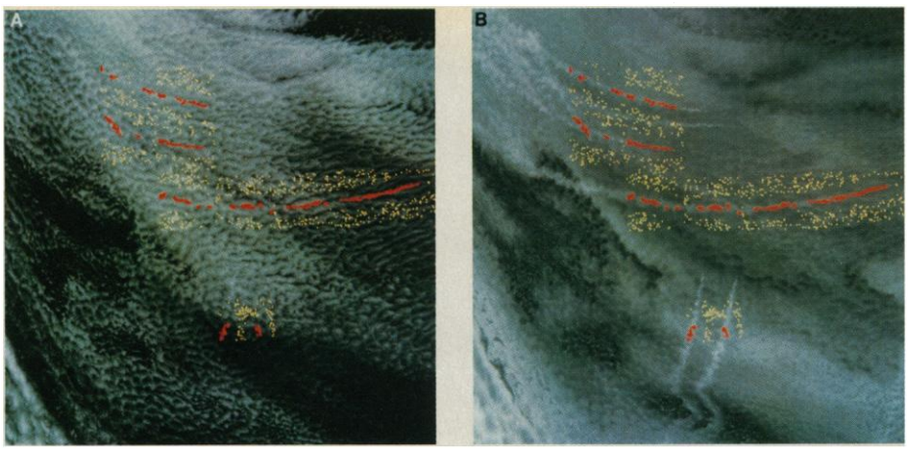

Fig. 2. Example of ship track identification (highlighted line segments) and randomly selected sample of noncontaminated clouds (bright dots): (**A**) superimposed on the image of 0.63-μm reflectivity and (**B**) superimposed on the image of 3.7-μm radiances.

subregions. This scale division was made to take advantage of the fact that groupings of 1 km by 1 km satellite fields of view within mesoscale subregions of large-scale cloud systems generally show similar radiative properties, which are taken to indicate a like similarity in the population of cloud properties for the groupings. Within the mesoscale subregions, fields of view that are contaminated by ship tracks were identified as those pixels with a 3.7-μm radiance in the upper tenth percentile for the subregion and that were connected to at least eight other pixels that also had 3.7-μm radiances in the upper tenth percentile so that the set of pixels formed a curvilinear line within the image. After the identification of contaminated pixels within a subregion, nearby noncontaminated fields of view were chosen at random from the remaining fields of view that constituted the subregion. Noncontaminated pixels were selected if they were separated from the contaminated fields of view by no less than approximately 10 km and no more than approximately 30 km. In addition, because the 0.63-μm reflectivity observed for individual fields of view depends strongly on the fractional cloud cover within the field of view and to a lesser extent on the distribution of cloud height, the selection of contamination-free fields of view was restricted so that the population of fractional cloud cover and cloud heights was similar to those of the contaminated fields of view. Thus the contamination-free fields of view were chosen so that their distribution of 11-μm radiances matched that of the contaminated fields of view.

Figure 2 shows the fields of view identified as contaminated and those selected at random for comparison. The radiative properties of contaminated and noncontaminated fields of view are shown in Fig. 3 for the uppermost ship track in Fig. 2. Figure 3 shows that the 0.63-μm reflectivities and 3.7-μm radiances of contaminated and noncontaminated fields of view are highly variable. This variability is the result of large variations in the amount of cloud liquid water and droplet sizes at small spatial scales. It masks the small increase in reflectivity at 0.63-μm for the contaminated clouds and makes the increase difficult to detect in the image.

The changes in cloud radiative properties for the three wavelengths shown in Figs. 1 and 3 are consistent with a shift to smaller droplets for the ship-contaminated clouds. At 3.7 μm water droplets both scatter and absorb radiation. The scattering cross section of a droplet is approximately proportional to its geometric cross section whereas the absorption cross section is approximately proportional to its volume. Thus the ratio of scattering to absorption increases as droplet radius decreases. Also, there is typically a sufficient concentration of droplets in stratocumulus so that, with the absorption that occurs, the radiative properties of the clouds are insensitive to droplet concentration (*10*). Thus, as droplet radii decrease, the additional scattering leads to increased cloud reflectivity (*11*). The enhanced radiances at 3.7 μm that identify the ship tracks in Fig. 1 are taken to be the result of shifts to smaller droplet sizes. At 11 μm, liquid water is a strong absorber. The amount of scattering is negligibly small. Furthermore, there are typically sufficient droplet concentrations so that marine stratocumulus emit like black bodies regardless of droplet size and concentration (*10*). Thus there is no change in thermal emission between contaminated and noncontaminated clouds in Fig. 1. Finally, at 0.63 μm liquid water is nonabsorbing. The scattering cross section is approximately proportional to the geometric cross section of the droplets. Thus, if a shift to smaller cloud droplets were to be compensated by an increase in droplet concentration so that the amount of cloud liquid water or the total droplet volume remained unchanged, then the amount of scattering would increase and thus cloud reflectivity would increase. Any decrease in reflectivity caused by the absorptive properties of the particulates that serve as the cloud-condensation nuclei is expected to be small compared with the increase in reflectivity caused by the shifts in droplet size and concentration (*12*). Although absorbing ash is undoubtedly present in ship exhaust, we presume that, as is the case for plumes from coal-fired power plants, the major source of cloud condensation nuclei is

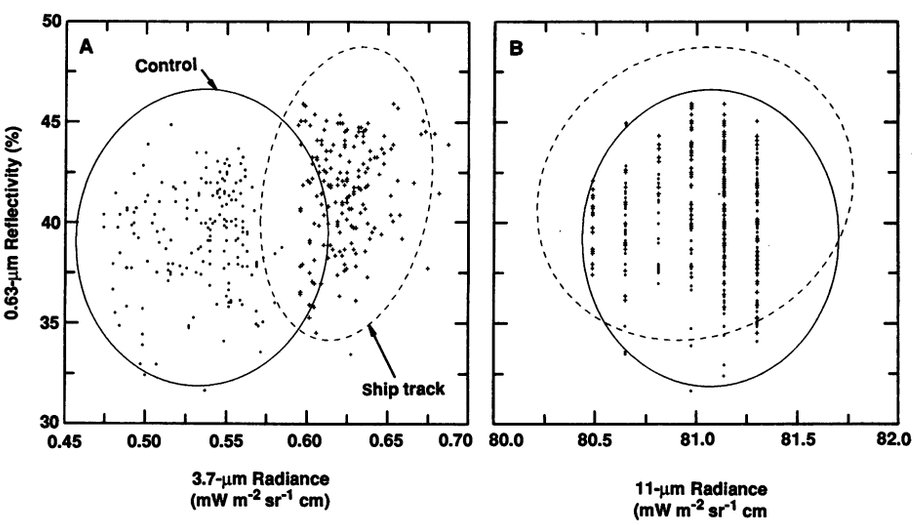

Fig. 3. Distributions of 0.63-μm reflectivity as a function of (**A**) 3.7-μm radiance and (**B**) 11-μm radiance for 1 km by 1 km fields of view contaminated by ship-stack exhaust (+) and those of randomly selected nearby noncontaminated fields of view (●). The distributions are for the uppermost ship track in Fig. 2. The solid and dashed ellipses represent fits at 2 standard deviations to the reflectivity and radiance distributions, which are taken to be joint Gaussian distributions.

through a gas-to-particle conversion of sulfur dioxide to form nonabsorbing sulfate particles (*13*).

For this study, data from four days (9 July and 19 November 1981, 3 April 1985, and 13 February 1986) were found to have ship tracks. Of the tracks found on these days, 15 independent tracks were found in which the ship contamination was contained wholly within a large-scale stratiform cloud layer and the population of cloud properties for contaminated and noncontaminated fields of view were nearly identical, as indicated by their distributions of 11-μm radiances. For this sample of tracks the increase in percent reflectivity at 3.7 μm was 3.9 ± 0.4 (SEM) and at 0.63 μm was 1.6 ± 0.7; the change in 11-μm radiance was 0.0 ± 0.05 mW m^{-2} sr^{-1} cm. The reflectivities were calculated as though the clouds were isotropic reflectors and the change in emission at 3.7 μm, which is expected to accompany the change in reflectivity, was ignored. The change in 3.7-μm reflectivity was underestimated by at most 10% by neglecting the accompanying change in emission.

The above changes are influenced by the fractional cloud cover found in the observations. To a first approximation, taking the ratio of the changes in reflectivity removes the effect of fractional coverage. The ratio of the change in 0.63-μm reflectivity to that at 3.7 μm for the 15 cases is 0.4 ± 0.8 (SD). Radiative-transfer calculations performed for several cloud models, in which the shift in droplet size compensates for a shift in droplet number so that the liquid water content is constant and no absorption is added, yielded ratios that ranged from 0.6 to 2.6 depending on droplet size and liquid water content. The observed changes thus seem to fall below the values expected on the basis of simple theoretical calculations. The shortfall might be due to extra absorption in the contaminated clouds, a decrease in the amount of liquid water for these clouds, or a change in cloud geometry so that the contaminated clouds have more surface texture.

The satellite observations reported here support the thesis that an increase in man-made aerosols will lead to an increase in cloud albedo. This finding differs from that previously reported for clouds over industrial centers of the Soviet Union where the polluted clouds had lower albedos (*14*). The differences may be due to much higher concentrations of absorbing particulates in the Soviet study.

Satellite observations may not elucidate the mechanisms by which aerosols affect droplet size, concentration, and absorptivity; nevertheless, they offer the opportunity for obtaining practical estimates for the net changes in cloud reflectivity. Because the effect of aerosols on cloud reflectivity appears to have a much greater influence on the earth's radiation budget than that due to the direct interaction of aerosols with solar radiation, and since the effect on cloud reflectivity may lead to changes in the earth's radiation budget that are comparable to those caused by the increased concentration of trace gases, the effect should be considered in assessments of potential climate change. This study has focused on changes in the maritime environment. Because continental environments have significantly higher concentrations of cloud-condensation nuclei and lower relative humidities, a similar study should be undertaken to determine the effects of stack effluents from industrial centers on continental stratiform clouds.

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Seasonal Mixing and Catastrophic Degassing in Tropical Lakes, Cameroon, West Africa

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Lethal gas releases from Lakes Nyos and Monoun in Cameroon seem to be more lacustrine than volcanic in origin. Both of these events occurred in August and were only 2 years apart. Data show that the period of deepest mixing and lake turnover also occurs during late summer in this region of tropical Africa. In addition, recent trends of decreases in both air temperatures and effective insolation relative to long-term means suggest that weakening of stratification, coupled with a predictable seasonal interval of reduced stability in August, may be responsible for the timing of these events.

ON 21 AUGUST 1986 A MASSIVE release of CO_2 from Lake Nyos claimed 1700 lives in northwest Cameroon (*1*). According to one theory (*1*), CO_2-rich gas of magmatic origin rising through the diatreme beneath the lake contacted local ground water. In turn, this ground water became the vehicle for gas transport into the lake's hypolimnion. Stable stratification prevented mixing of bottom water with surface water and allowed gas accumulation well in excess of atmospheric saturation. Some unknown disturbance of this unstable system culminated in the gas release. A similar model has been put forth to explain the 15 August 1984 gas release at Lake Monoun, 95 km southeast of Lake Nyos (*2*). What is most intriguing about this phenomenon of lethal gas release from lakes is that both events occurred in August, just 2 years apart. The timing and limnologi-

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