Reflected Radiance Measured by NOAA 3 VHRR as a Function of Optical Depth for Saharan Dust

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ABSTRACT

A near-linear relationship is described between aerosol optical depth for Saharan dust over the eastern tropical Atlantic Ocean and radiance measured aboard the NOAA 3 satellite by the VHRR.

1. Data analysis

Over the past 10 years, outbreaks of dust from North Africa have become observable on conventional satellite pictures. The dust appears greyish white on the visible channel photographs, somewhat resembling cirrus clouds but with a distinctive gossamer texture which one associates with high dust concentrations and increased turbidity. Such observations suggest that the amount of dust present should correspond in some

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fashion to the intensity of radiance (or brightness) measured by a visible channel satellite radiometer.

Recently, Griggs (1975) and Fraser (1976) have described a linear relationship between aerosol optical depth, aerosol concentration and the reflected radiance measured by ERTS satellite at solar wavelengths. Both these authors make use of theoretical models to substantiate observations. Fraser, however, deals exclusively with Saharan dust, basing his calculations on measurements obtained from a combination of ERTS radiance and ground-based sunphotometer measurements made near the Mauritanian Coast during August 1972. Griggs also finds that the Saharan dust measurements treated by Fraser agree with the linear relationships he obtained between reflected radiance and aerosol content for satellite observations made over California. The purpose of this note is to further establish quantitatively the variation of reflectivity with dustiness in terms of the measured optical depth at the ground and the reflected intensity received by the VHRR visible channel instrument aboard the NOAA 3 satellite during the 1974 GATE field experiment.

During GATE surface-based optical depth measurements were made at a network of sunphotometer sites using manually operated dual-channel Volz instruments ($\lambda = 0.50$ and 0.88 μm) or the Eppley KH model sunphotometers ($\lambda = 0.38$ and 0.50 μm). These data are currently summarized in two publications prepared for the GATE archives as part of the subprogram for radiation (Prospero *et al.*, 1976; Cram, 1976). We have analysed the VHRR brightness data obtained from eight passes made over the GATE A/B scale region in July and August 1974 during periods of apparently heavy dust outbreaks.

Reflected radiances were calculated from the observed brightness values, which are recorded as an analog voltage aboard the spacecraft and subsequently processed to digital form in DN units on a gray scale 0 to 255, higher numbers representing lower brightness. These digital values can be converted to units of brightness. For convenience we will express brightness values in conventional (foot-lamberts, fL) units in order to facilitate comparison with established calibration curves which have been provided by the National Environmental Satellite Service (NESS) for this instrument. Initially, one calibrates the brightness scale against a reference voltage wedge (black ≈ -0.25 V) measured internally aboard the satellite and recorded along with the raster information on the data tapes. Conversion from fL to radiance values proceeds by following methods outlined by Jacobowitz[2] and by Gruber (1977) for the NOAA 2 SR radiometer. The NOAA 3 visible channel has a spectral response between 0.58 and 0.74 μm wavelength with a flux-weighted average wavelength at 0.66 μm. Integration over both spectral response curves of the human eye and of the calibration source used by the manufacturer (RCA) and application of a correction for the amount of energy of the calibrating source within the spectral range of the radiometer (17.5% for NOAA 3) yields a conversion constant of 0.00434 W m^{-2} sr^{-1} fL^{-1}. The filtered solar constant is 12.2% of the full flux value. This conversion factor is slightly dependent on the spectral distribution of radiance reaching the satellite, since the unattenuated spectral solar constant was used as a weighting factor in its determination. The error is not likely to be very large in view of the near neutrality of extinction for Saharan dust (Carlson and Caverly, 1977; henceforth referred to as CC). As an additional check against independent measurements, reflected solar radiance derived from data provided by the NOAA 2 scanning radiometer for a 2.5° latitude by longitude area over the Sahara desert on 30 July 1974[3] was compared with the NOAA 3 VHRR measurements for that same area at approximately the same time on that day. Assuming isotropic reflectance the ratio of the reflected irradiance to the incoming solar flux (spectral albedo) was 34.2% for NOAA 2 SR and 29.7% for NOAA 3 VHRR.

In order to determine the clear sky radiances, a method for screening out cloud was adopted. The first step was to examine the corresponding visible satellite photograph for the NOAA 3 VHRR and identify regions where there was *ostensibly* no cloud. In order to handle the immense quantity of brightness data and to eliminate noise, the original 1 km resolution pixels were composited by a linear average to form a data base consisting of elements made up of 24 of the original pixels. Each composite element was therefore formed from six partially overlapping spot values and four successive scan lines covering an area about 15 km^2 on the earth.

Subsequently, the *clear sky* brightness over selected areas was determined from criteria based on histograms of brightness values within visibly cloud-free areas on the satellite photograph. Fig. 1 is an illustration of such a histogram obtained from an approximately 1500 km^2 area near Sal Island on 9 July 1974. Although seemingly clear areas on a satellite photograph may contain small amounts of cloud and ocean surface whitecaps, undetectable in the picture, the most regular trade cumulus canopies are likely to contain some gaps. The next step was to determine a clear sky brightness value which we assumed to be the reflectance from an elemental area lying within such a cloud-free zone and the reflectance associated with the highest (darkest) contiguous step in the histogram. In clear regions the histograms were typically narrow (as in Fig. 1) and the spatial gradients of brightness quite smooth and weak. On the other hand, areas exhibiting

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[2] Jacobowitz, H., 1975: Memo for the record: Calibration of the visible channel of the NOAA-2 scanning radiometer. 15 January, NOAA/NESS, Washington, D. C. (internal circulation only).

[3] Data furnished by A. Gruber, NESS.

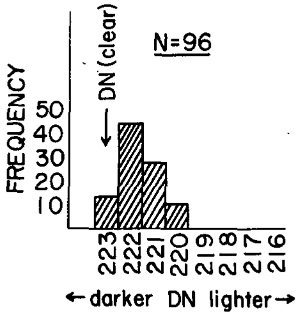

FIG. 1. Histogram of brightness (DN) values from NOAA 3 VHRR for an apparently clear area near Sal Island, 9 July 1974. The darkest value of 223 was assumed to represent the clear sky brightness at that point.

even small amounts of cloud on the photograph produced a broader histogram and contained patterns which were much more irregular and chaotic than those in areas with no visible cloud. Therefore histograms, such as those characterized by the narrow spread illustrated in Fig. 1, were considered as evidence of only small amounts of cloud contamination and the highest (darkest) DN value was identified with the true clear sky radiance over an ocean surface.

In practice the histograms were evaluated subjectively by inspection. This procedure was applied to the brightness fields and transposed to geographical maps containing satellite orbit information (track, solar zenith angle, nadir angle and azimuth angle with the solar plane).

Because of the dependence of brightness on the angular parameters (particularly those of solar and nadir angle), we needed to determine a set of correction factors for various solar, azimuth and nadir angles and for various aerosol optical depths at $\lambda=0.66$ μm. These corrections were derived from calculations made with a Monte Carlo radiative transfer model recently described by Wendling (1977). Measured radiances obtained by satellite were normalized to a solar zenith angle of 45° and a satellite nadir angle of 0° using the Monte Carlo model results. Photon counts were averaged over a 60° azimuthal arc, 0–60° azimuth for viewing angles facing the sun and 180–240° azimuth for viewing angles in the opposite direction. Optical properties of the dust used in the Monte Carlo calculations were based on measured size spectra and the index of refraction of Saharan dust at $\lambda=0.66$ μm ($n=1.54-0.0025i$), a value inferred from the results of CC. Surface albedo for the ocean was taken as a function of solar zenith angle according to the results of Payne (1972). The aforementioned brightness pattern was then modified by the Monte Carlo corrections in areas not affected by sunglint. No consideration was given to the effect of wind speed on ocean reflectivity.

The uncertainty inherent in this method is probably about ±1 DN unit (~45 fL). Results are more strongly sensitive to error at small optical depths where an uncertainty of even ±1 DN unit can affect the determination of optical depth by introducing a relatively large error in the aerosol contribution to the reflectance. High dust concentrations may also mask the presence of clouds because of the decreasing contrast between cloud and dust; however, under such circumstances the aerosol optical depth is already very large, and consequently, the relative error in τ_d would still be small. Sunglint is also troublesome although its location can be predicted by model calculations and can therefore be avoided.

2. Results

Ground-based measurement of aerosol optical depth τ_d were interpolated logarithmically to $\lambda=0.66$ μm between readings for the Volz sunphotometers which provided most of the observations in Fig. 2. In the few instances where Eppley measurements were used, τ_d was taken to be that at $\lambda=0.50$ μm. In either case, the weak wavelength dependency between τ_d and λ for

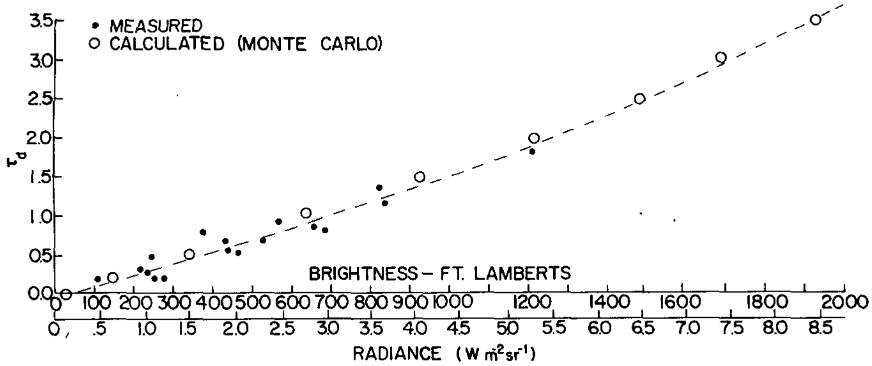

FIG. 2. Aerosol optical depth τ_d versus reflected radiance N (W m^{-2} sr^{-1}) or brightness (fL) normalized to 0° nadir angle and 45° solar zenith angle. Black dots correspond to observed optical depth at $\lambda=0.66$ μm and open circles to optical depths calculated from Monte Carlo method for a reflecting ocean surface and an index of refraction $n=1.54-0.0025i$. The dashed line drawn to best fit all the data has a functional relationship described in the text.

Saharan dust enables such approximations to be made without incurring serious error.

Altogether a total of 17 ground observations were available for which the normalized radiances N (W m^{-2} sr^{-1}) were plotted as a function of aerosol optical depth at the location of the sunphotometer site. Likewise, Monte Carlo calculations of radiance versus aerosol optical depth are plotted in the figure showing very good agreement between theory and observations and closely fitting the curve

$$\tau_d = -0.15 + 0.38N + 0.005N^2 (\tau_d \leqslant 3.5).$$

At increasing optical depths above 3.5 the rate of increase in reflected radiance diminishes with increasing optical depth and presumably approaches a limit of zero for very large values of τ_d. The rapid decrease in the sensitivity of brightness to changes in optical depth is dependent on the absorptivity of the dust, the latter being rather small at this wavelength. Moreover, with increasing optical depth, the backward scattering peak for single aerosol particles is increasingly diffused for the medium of particles, resulting in increasing side scatter toward the satellite radiometer, which is at a large angle to the backward reflection peak. Consequently, there continues to be a rapid increase in the amount of radiance detected by the satellite with increasing optical depths for dust out to rather large values of τ_d.

Optical depth for a given aerosol size distribution and chemical composition is directly related to total mass concentration. A parametric formula expressing a relationship between total mass loading and optical depth for Saharan dust over the eastern Atlantic is given by CC, i.e., $M = 3.75\ \tau_d$, where M is the mass (g m^{-2}) and τ_d the aerosol optical depth at about 0.5 μm. From ERTS data Fraser (1976) calculated a total mass loading of 1.6 g m^{-2} for an optical depth of 0.5, in reasonable agreement with a value of 1.9 g m^{-2} obtained from the forementioned relationship for that same value of τ_d. Griggs (1975), on the other hand, obtains much smaller yields of dust loading for equivalent values of τ_d, presumably because of the smaller numbers of large particles in the California dust spectra.

Generally, dust becomes visible on conventional satellite photographs where τ_d begins to exceed a value of about 1–1.5. The largest value measured during GATE was 1.8 on 30 July at Sal Island. As on other such occasions, the brightest (dustiest) region on the picture was located to the north of Sal Island, where clear sky brightness values approaching 2000 fL were sometimes observed, suggesting optical depths in excess of 3.0 and dust loadings of more than 10.0 g m^{-2}. Such large values are probably not uncommon in the heavier dust outbreaks though they cannot be verified independently with existing data.

The sensitivity of reflectance to dust loading illustrated by Fig. 2 is somewhat fortuitous since the reflectance depends most strongly upon the ratio of absorption cross section to scattering cross section (the absorptivity), which is a function of wavelength. CC show that this ratio increases rapidly with decreasing wavelength below about 0.6 μm so that at wavelengths below about 0.5 μm, the reflectivity would respond to an increase in dust content by *decreasing*. At shorter wavelengths, therefore, the diminution of reflected energy would be manifested by a *darkening* of the photograph in dusty regions, suggesting that while wavelengths greater than 0.6 μm may be ideal for examination of atmospheric dust content, a satellite instrument operating near 0.5 μm may be best suited for studies where Saharan dust might otherwise interfere with the desired observation of some other phenomenon.

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