Satellite Observations of Atmospheric Aerosols During the EOMET Cruise

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ABSTRACT

Measurements of the atmospheric aerosol optical thickness were made during the 1977 EOMET cruise across the Atlantic Ocean and the Mediterranean Sea. These data were obtained at the same time as NOAA 5 and GOES visible radiance measurements in the vicinity of the ship. Linear relationships between the upwelling radiance and the aerosol optical thickness were found for each satellite, confirming earlier Landsat results. Differences in the relationships for each satellite are attributed to differences in the radiometric calibrations of the satellite sensors.

1. Introduction

The atmospheric marine boundary layer is of considerable importance to Navy operations. Of particular interest, with the increasing use of electro-optical systems, is the nature and distribution of aerosols over the oceans. In order to provide further information about the aerosols and other meteorological parameters in the marine boundary layer, the Naval Research Laboratory conducted an Electro-Optical Meteorology (EOMET) cruise, 15 May–6 June 1977, across the North Atlantic Ocean and Mediterranean Sea. This cruise offered a good opportunity to further investigate the satellite technique developed by Griggs (1975, 1977) to measure the atmospheric aerosol content over oceans. This technique relates the upwelling visible radiance measured by the satellite to the atmospheric aerosol optical thickness. Since 60% of the aerosols are typically in the lowest 1 km, and 90% in the lowest 3 km, it is clear that the satellite measurements can provide information of considerable importance to Navy operations. The previous studies were based on Landsat data, but for this investigation the NOAA and GOES satellites were used.

2. Previous Landsat results

Previous results using Landsat 1 data (Griggs, 1975) and Landsat 2 data (Griggs, 1977) have shown that a linear relationship exists between the upwelling radiance in the visible region and the aerosol content. Data have been obtained at several sites, the largest data set being for the Pacific Ocean at San Diego for Landsat 2 overpasses. These results are shown in Fig. 1. The radiances are determined from the Landsat digital data (densitometry of the black and white imagery is not accurate enough for intercomparison of different images), and the aerosol content values are determined with ground-based Volz sun photometer measurements at the time of the Landsat overpass. The aerosol content is defined in terms of the Elterman (1965) model vertical aerosol

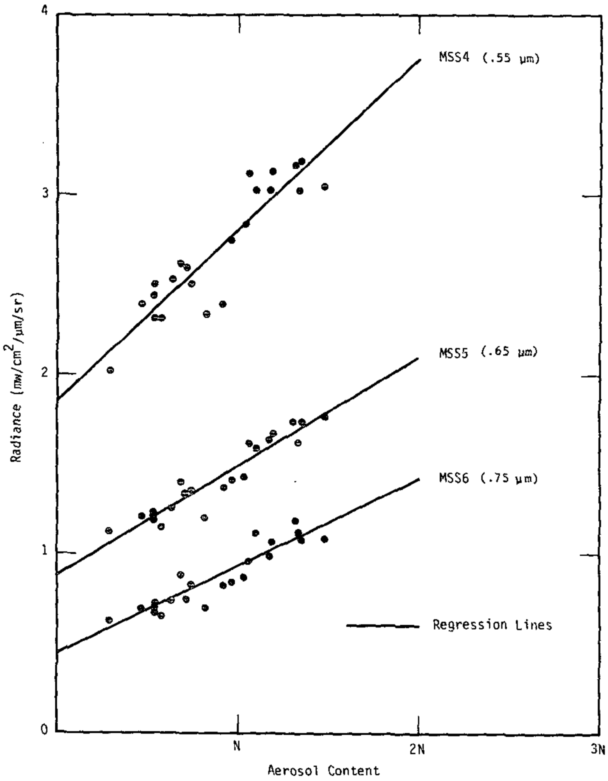

Fig. 1. Landsat 2 ocean radiances versus aerosol content. The radiances are for nadir viewing normalized to a sun zenith angle of 63°.

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optical thickness; i.e., the aerosol content is given by the ratio (measured aerosol optical thickness at wavelength λ to the model aerosol optical thickness at wavelength λ) $\times N$—a value of $2N$ for the aerosol content indicates that the optical thickness is twice that of the Elterman model. In the results reported here, measurements of the aerosol optical thickness were available only at 0.5 μm, so that all radiances measured by the different radiometers are plotted against aerosol content where N indicates an aerosol optical thickness of 0.213 (the Elterman model value) measured at 0.5 μm.

The relationships appear best for multispectral scanner (MSS) channels MSS 5 and MSS 6; this is probably due to the fact that the radiance in MSS 4 is affected by suspended matter in the water. Fig. 1 does not show MSS 7 data, since the digital data for this channel are uncertain owing to NASA procedures for producing Landsat 2 computer compatible tapes.

3. Approach

Arrangements were made for sun photometer measurements of the atmospheric aerosol optical thickness to be taken daily, weather permitting, on board the USNS *Hayes* (EOMET cruise vessel) at times as nearly coincident as possible with the overpasses of NOAA 5 (0800–1000 LST) and at 1600 GMT, when GOES 1 digital data are routinely recorded and stored. The radiances measured by the satellites must be modified in order to compare them with the Landsat values shown in Fig. 1. The Landsat radiances are for the multispectral scanner spectral bandpasses and for nadir viewing. The NOAA 5 and GOES 1 have slightly different bandpasses and, in general, the radiances of interest are not obtained in the nadir direction. These radiances are normalized to the Landsat viewing and sun angle conditions by means of theoretical calculations with an atmospheric scattering code (Dave and Gazdag, 1970) which was previously used in support of the Landsat study.

4. Data analysis

The sun photometer data had to be carefully reviewed since measurements are difficult to make on board ship due to the motion of the ship. This is especially true for the measurement of the airmass; fortunately, this can be precisely calculated from knowledge of the location of the ship and the time.

The location of the ship as a function of time and the orbital parameters of the NOAA 5, which is in a polar orbit, are used to determine the respective locations of ~~the ship and~~ the satellite at the time the satellite radiance measurement is acquired. Then, using spherical trigonometry, the sun zenith (θ_0) and azimuth (ϕ) angles and the viewing angle (θ) from the satellite to the ship are calculated. For the geosynchronous GOES 1, which is at a fixed location, the required angles are similarly calculated. These angles are used as input to the Dave code which is used to normalize the measured radiance to the standard conditions used for the Landsat data, *viz.*, $\theta_0=63.3°$, $\phi=0$, $\theta=0$. The calculations are made for each pair of satellite radiance and aerosol content observations, using the measured aerosol content as input to the code. The aerosol model used in the code is one that gave good agreement with the Landsat 2 data, i.e., a Junge size distribution with $\nu=4.0$ and refractive index $n=1.5$. Thus, the normalized radiance (I) is given by

$$I=I_m\frac{I_c(0,63.3°,0,N_m)}{I_c(\theta,\theta_0,\phi,N_m)},$$

where I_m is the measured radiance, I_c the calculated radiance and N_m the measured aerosol content.

The calculations are performed at 0.67 μm for the NOAA 5 Scanning Radiometer (SR) and at 0.64 μm for the GOES Visible Infrared Spin Scan Radiometer (VISSR).

The satellite data were obtained in digital form from the National Environmental Satellite Service (NESS) of NOAA. The SR data were available only in the mapped format (with 20 km resolution) for this investigation, and did not provide all the resolution elements actually measured during the satellite overpasses. Another shortcoming of the SR data is the fact that the SR output is subject to a nonrandom noise which cannot be readily eliminated. In an attempt to minimize these effects, each SR radiance reported here is the mean of a 5×5 block of pixels centered on the calculated ship location. The VISSR radiances (with 6 km resolution) reported here are also the means of 5×5 blocks of pixels. The radiances are given in units of mW cm^{-2} μm^{-1} sr^{-1}, and are based on calibration data obtained from NESS, converting digital counts to foot-Lamberts, in the case of the SR, and directly into radiance units in the case of the VISSR.

5. Results

The weather during the cruise was generally quite good, enabling coincident sun photometer and satellite measurements to be obtained on several occasions. The GOES coverage of the Atlantic Ocean is good only to about 25°W, which was reached by the USNS *Hayes* on 24 May 1977. In these first 10 days, sets of data were obtained on six occasions for the GOES. During the same time period, six sets of data were also obtained for NOAA 5 overpasses. However, after 24 May 1977, 10 more days were spent at sea, but only three more sets of data were obtained for the NOAA 5 overpasses.

The GOES VISSR data, plotted in Fig. 2, show an excellent linear relationship, as anticipated from the Landsat results, and show that normalization procedures with the Dave code are satisfactory.

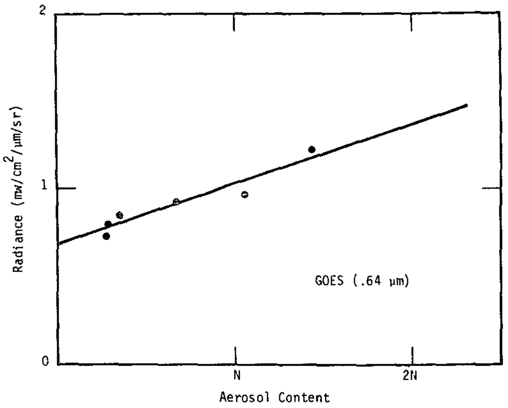

FIG. 2. As in Fig. 1 except for GOES ocean radiances.

The NOAA 5 SR data were not expected to be very useful due to their format and noise problems, as described above. However, in spite of these shortcomings, the relationship shown for the SR radiances in Fig. 3 is remarkably good. A linear relationship can probably be inferred. The crosses show an enhanced radiance due to sun-glitter, and demonstrate that observations should be made away from the sun, except close to the nadir as illustrated by the circle.

In comparing these results with those of Landsat 2, taking into account the wavelength differences, it is found that for the SR data, the radiance value for $N=0$ is as expected (this value is independent of the aerosol properties, and represents a pure molecular atmosphere), but that the other radiances are lower than expected. This can be due to the aerosol properties being different from those of the Landsat San Diego data, or to uncertainties in the radiometric calibrations in each satellite. However, in the Landsat study, data obtained at Adrigole, Ireland, for Atlantic Ocean aerosols showed good agreement with the San Diego data. The same study showed that differences also existed between the Landsat 1 and Landsat 2 results at San Diego, and it was concluded that they were due to differences in the radiometric calibrations of the two satellites. It is believed that similar calibration problems are responsible for the SR and Landsat differences. Indeed, in examining the VISSR results in Fig. 2, it is found that both the intercept and slope of the line are significantly different from those predicted from the Landsat data, suggesting again that the reason is due to the radiometric calibrations.

It should be understood that the upwelling radiance depends on the aerosol optical properties, such as size distribution and refractive index, and on other parameters such as surface reflectivity, wavelength, sun angles and satellite viewing angles. It was shown earlier (Griggs, 1975) that the vertical distribution of aerosols does not significantly affect the upwelling radiance. The effect of varying surface reflectivity is minimized by avoiding observations in areas of sun glitter. Thus, some scatter in the radiance values shown in the results is expected, mainly from variations in the size distribution and refractive index; these effects are currently being examined theoretically and will be the subject of a future publication. Of course, some scatter is due to experimental error both in the radiances and in the sun photometer, as discussed earlier by Griggs (1975). The aerosol content can be measured with an accuracy of ±5–10%, and the MSS radiance can probably be determined with an accuracy of about ±0.06 mW cm^{-2} μm^{-1} sr^{-1}.

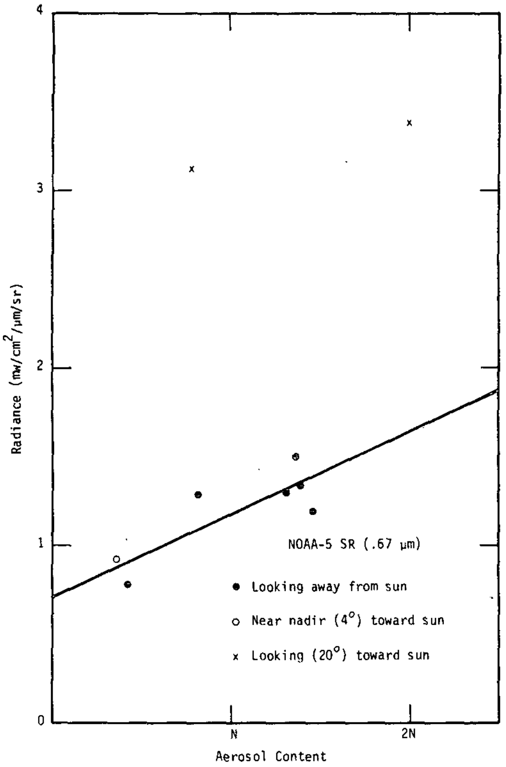

FIG. 3. As in Fig. 1 except for NOAA 5 ocean radiances.

6. Conclusions

A linear relationship between the upwelling visible radiance, as observed by the Landsat MSS, and the atmospheric aerosol content, has also been found for the GOES VISSR and the NOAA 5 SR. The relationships are slightly different for each satellite. These differences are attributed to differences in the radiometric calibrations of the satellites and points to the necessity of precise radiometric calibrations of satellite radiometers if they are to be used in the future for aerosol measurements. Without precise calibration each satellite would have to be empirically calibrated with lengthy periods of ground truth measurements.

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