JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 97, NO. D13, PAGES 14,545–14,549, SEPTEMBER 20, 1992

Directional and Spectral Reflectance of the Kuwait Oil-Fire Smoke

MICHAEL D. KING

Laboratory for Atmospheres, NASA Goddard Space Flight Center, Greenbelt, Maryland

The angular reflectance pattern of the Kuwait oil-fire smoke was measured from an aircraft at 13 discrete wavelengths between 0.5 and 2.3 μm. Measurements at 0.75 and 1.64 μm showed that the reflectance of the smoke layer was about 12% in the nadir direction with considerable limb brightening toward the horizon. Furthermore, these observations revealed a backscattering maximum in the antisolar direction and an enhanced scattering near the rainbow direction. These characteristics suggest that the smoke layer 90 km downwind of the Kuwait oil fires was composed of a significant number of oil drizzle droplets that scatter solar radiation as a layer composed of spherical particles.

1. Introduction

During the latter half of February 1991, Iraqi soldiers detonated 732 oil wells in Kuwait, 611 of which were set ablaze [*Shannon*, 1991]. Since that time, numerous smoke plumes generated by these fires have been observed and monitored by the NOAA-10, NOAA-11, and Landsat polar orbiting satellites and the Meteosat geosynchronous satellite [*Limaye et al.*, 1991, this issue; *Canby*, 1991]. Between May 16 and June 12 a Kuwait Oil Fire Smoke Experiment was conducted in the Persian Gulf region [*Hobbs and Radke*, 1992], with coordinated acquisitions by the Landsat thematic mapper [*Cahalan*, this issue]. During this time, some 550 oil wells were still burning in Kuwait, the largest concentration of smoke plumes arising from the Greater Burgan oil field just south of Kuwait City.

Along much of the coast, the smoke plume remained confined to a strip about 50 km in width on a given day, widening and thinning out as it moved off the Arabian peninsula toward the Gulf of Oman and India. Besides being confined to a horizontal band some tens of kilometers in width that could wander over a much wider area depending on wind direction and speed, the smoke plume was much more restricted in the vertical, occurring between a well-defined base and top. It was generally capped by a strong temperature inversion, typically between 3 and 4 km, which was likely augmented by solar heating in the upper part of the dark plume [*Browning et al.*, 1991; *Bakan et al.*, 1991]. Its base was generally located at an altitude of 0.5 km and was also quite flat after the layer had stabilized some 100 km downwind of the burning oil fields.

The intent of this paper is to describe results of airborne measurements of the angular reflectance pattern of the smoke layer obtained some 90 km downwind of the Greater Burgan oil field, located at 29°N, 48°E. The observations were acquired from the University of Washington's C-131A research aircraft on May 18, 1991, as the aircraft flew a clockwise circular orbit above the Kuwait oil-fire smoke. The purpose of this flight pattern was to obtain measurements of the full bidirectional reflectance pattern of the smoke layer at 13 discrete wavelengths between 0.5 and 2.3 μm. The measurements were obtained with the cloud absorption radiometer (CAR) initially developed for measuring the angular distribution of scattered radiation deep within a cloud layer [*King et al.*, 1986]. In this paper we present measurements of the bidirectional reflectance pattern of the Kuwait oil-fire smoke obtained at 0.75 and 1.64 μm, and contrast these measurements with the radiative properties to be expected from an optically thick absorbing medium composed of oil droplets, soot, and salt.

Paper number 92JD01043.
0148-0227/92/92JD-01043$05.00

2. Results From Observations

Measurements of the diffuse radiation field both reflected and transmitted by the oil-fire smoke were obtained with the cloud absorption radiometer mounted in the nose of the aircraft. This multispectral radiometer scans in a vertical plane on the right-hand side of the aircraft from 5° before zenith to 5° past nadir (190° aperture). The first seven channels of the radiometer were continuously and simultaneously sampled, while the eighth registered channel was selected from among the six channels on the filter wheel. Since the scan rate of the radiometer was 1.67 Hz, each minute of flight duration resulted in 100 measurements of the angular intensity field for each of the first seven channels and, typically, 12 measurements for each of the six filter wheel channels. Thus with a clockwise circular flight pattern (Figure 1), the entire reflectance pattern from nadir to the horizon was obtained, as was much of the transmittance pattern from near zenith to the horizon.

The smoke layer on May 18 was the highest altitude that we observed during this month-long experiment, and required that the aircraft fly at 540 mbar in order to be well above the smoke layer. Each orbit of the aircraft took 2.5 min to complete and consisted of a circle about 3 km in diameter. This resulted in reflected solar radiation measurements being acquired for 250 scans of the radiometer for each of the first seven channels (0.5–1.27 μm) and 30 scans for each of the filter wheel channels (1.55–2.29 μm). Because of the small but significant spatial variations of the smoke layer, the measured reflectance at nadir ($\theta = 0°$) varied with a standard deviation of a few percent over the 1.25 min required to complete half an orbit. Thus all measured intensity measurements were scaled to match the nadir measurement obtained from the scan in the backscattered plane ($\phi = 180°$).

Plate 1 illustrates the reflection function of the smoke layer as a function of zenith (θ) and azimuth (ϕ) angle at two wavelengths (0.75 and 1.64 μm), where the reflection function is formed from a ratio of the reflected intensity $I(0, -\theta,$

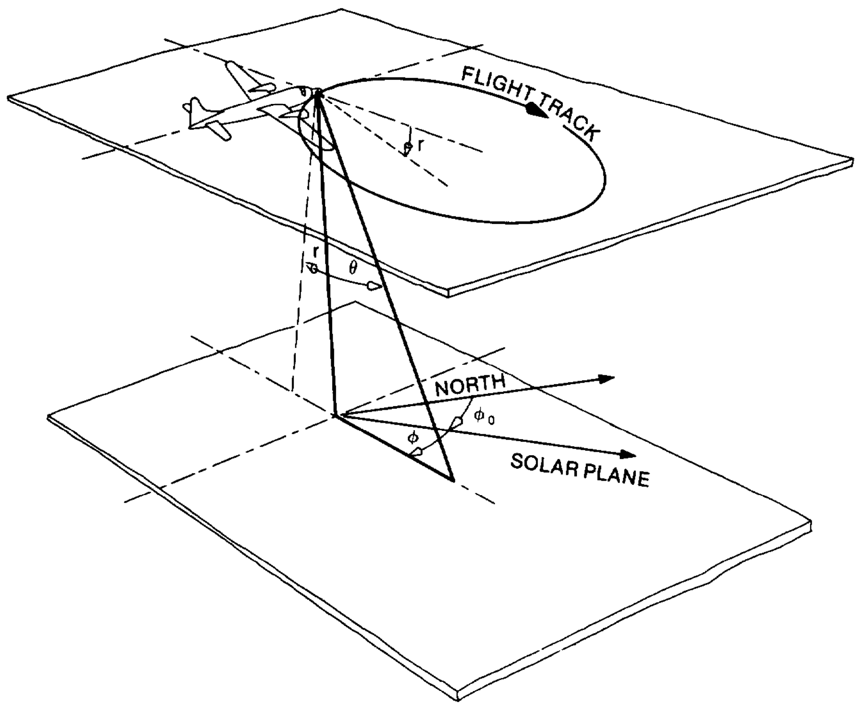

Fig. 1. Schematic illustration of the relationship between the zenith angle θ and relative azimuth angle ϕ of radiation reflected by the Kuwait oil-fire smoke, and the roll r and nadir viewing angle of the aircraft, for a clockwise circular flight track above the smoke.

ϕ) and the solar flux density incident on the top of the atmosphere F_0, and is defined by

$$R(\theta,\ \theta_0,\ \phi) = \frac{\pi I(0,\ -\theta,\ \phi)}{\mu_0 F_0} \tag{1}$$

where μ_0 is the cosine of the solar zenith angle θ_0 and ϕ is the relative azimuth angle between the direction of propagation of the emerging radiation and the incident solar direction (see Figure 1). The calibration of the CAR was performed at Goddard prior to the experiment by viewing the output of a 122-cm integrating hemisphere and a 183-cm integrating sphere, each of which was coated with 12–14 coats of a highly reflecting $BaSO_4$ paint and internally illuminated by a series of up to 12 quartz-halogen lamps (see *King et al.* [1986] for further details). The measurements reported here were obtained at 0555 UTC when $\theta_0 = 39°$. At both wavelengths the reflection function of the smoke layer was about 12% in the nadir direction with considerable limb brightening toward the horizon, a result to be expected from an absorbing aerosol layer exhibiting low orders of scattering [*Chandrasekhar*, 1960; *van de Hulst*, 1980].

Of particular interest in these measurements is the backscattering maximum that occurs in opposition to the sun (antisolar direction, where $\theta = 39°$, $\phi = 180°$) and the enhanced scattering near nadir that occurs when the scattering angle $\Theta \simeq 143°$. These characteristics, which occur at both 0.75 and 1.64 μm, correspond to the well-known glory and rainbow features of single scattering by spherical particles. These measured reflectance characteristics, taken together, suggest that the Kuwait oil-fire smoke within 100 km of the source is composed at least in part of large spherical particles and that the aerosol optical thickness $\tau_a \leq 8$. We draw this conclusion from corresponding calculations of the reflection function of liquid water clouds in the principal plane of the sun as a function of optical thickness, single scattering albedo, and solar zenith angle [*Hansen*, 1969, 1971]. These computations show the rapid change from limb brightening with a well-defined glory and rainbow for small optical thicknesses to limb darkening with no rainbow feature for large optical thicknesses. Furthermore, direct observations of the aerosol optical thicknesses obtained from the C-131A on this day and at a location close to that of our observations confirm that $1 \leq \tau_a \leq 2$ for wavelengths $0.4 \leq \lambda \leq 1.0$ μm [*Pilewskie and Valero*, this issue].

The rainbow is produced by refraction at the surface of a spherical particle, followed by one internal reflection and refraction of the exiting ray. The rainbow angle (Descartes ray) at which the reflection function of the smoke layer is enhanced is directly related to the real part of the refractive index of the spherical particles within the smoke plume, and is given by

$$\Theta = 2\theta_i - 4\theta_t + 180° \tag{2}$$

where the angles of incidence (θ_i) and transmission (θ_t) are determined by the refractive index (m) as follows [*Bohren and Huffman*, 1983]:

$$\cos\ \theta_i = [(m^2 - 1)/3]^{1/2} \tag{3}$$

$$\sin\ \theta_i = m\ \sin\ \theta_t \tag{4}$$

from which it follows that $m \simeq 1.37$ when $\Theta \simeq 143°$. The single scattering albedo of the gray smoke layer downwind of the fires was measured in situ by aircraft and found to be generally between 0.5 and 0.6 in the visible wavelength region [*Johnson et al.*, 1991; *Weiss and Hobbs*, this issue], a fact that necessarily reduces the orders of scattering and

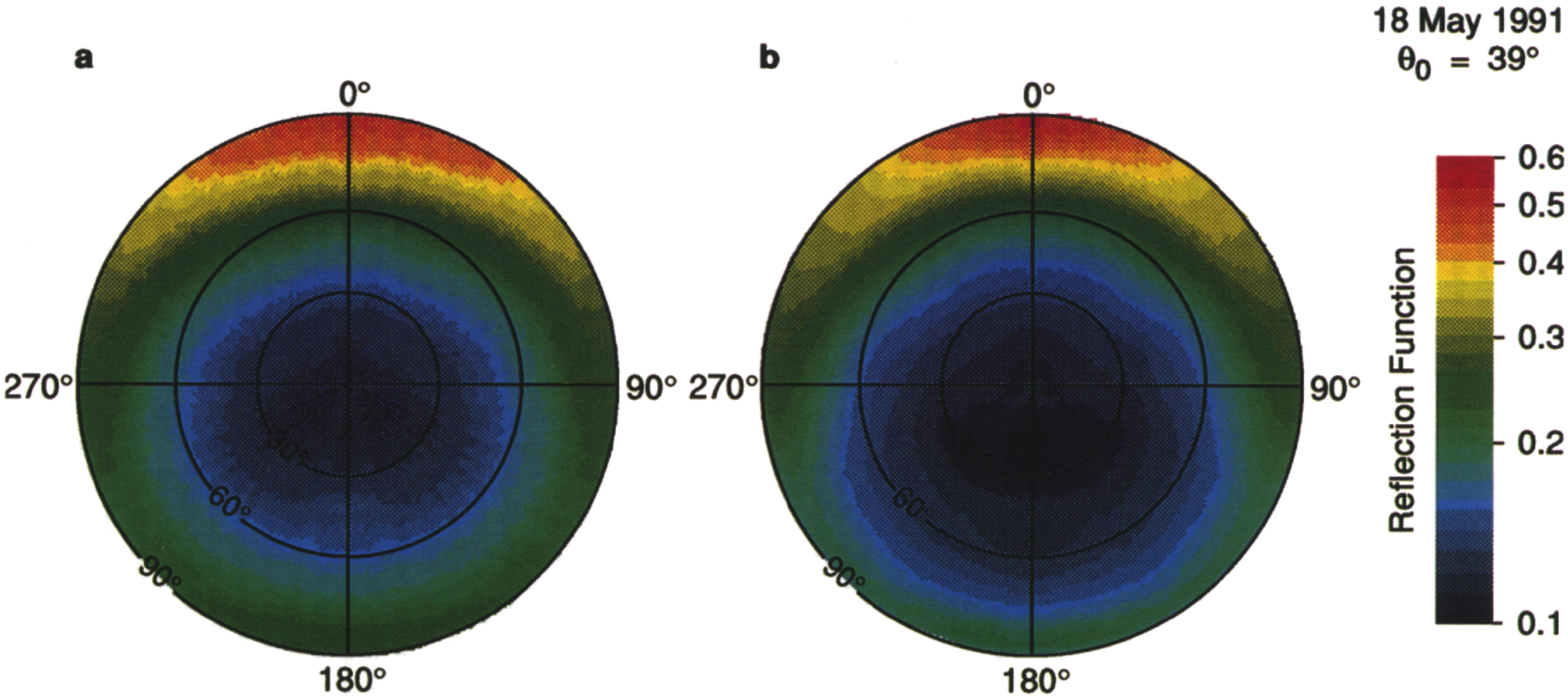

Plate 1. Images of the reflection function of the Kuwait oil-fire smoke obtained at (*a*) 0.75 μm and (*b*) 1.64 μm from the C-131A aircraft on May 18, 1991. These images were obtained approximately 90 km downwind of the Greater Burgan oil field when the solar zenith angle $\theta_0 = 39°$. Note the enhanced reflection in the antisolar direction ($\theta = 39°$, $\phi = 180°$) and at nadir, corresponding to the glory and rainbow features of light scattering by spherical particles, respectively.

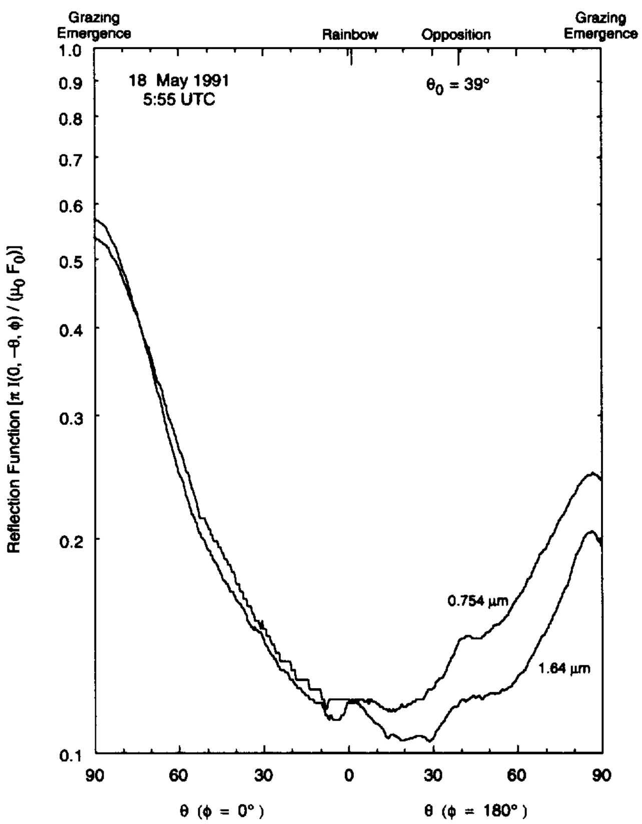

Fig. 2. Measured reflection function of the Kuwait oil-fire smoke in the principal plane of the sun at 0.75 and 1.64 μm. These results correspond to the cross section through the azimuth plane containing the sun of the images presented in Plate 1, and quantify the magnitude of the limb brightening and enhanced reflection in the opposition (glory) and rainbow (nadir) directions.

hence contributes to retaining the single scattering features that we observed.

To further examine the angular reflectance characteristics of the Kuwait oil-fire smoke, we constructed the reflection function of the smoke layer as a function of zenith angle in the $\phi = 0°$ and 180° plane (i.e., the vertical plane containing the sun). These results, presented in Figure 2, represent two of the many scans of the cloud absorption radiometer shown in Plates 1*a* and 1*b*. This figure clearly demonstrates the magnitude of the reflection function of the smoke layer 90 km downwind of the Greater Burgan oil field at 0.75 and 1.64 μm. In the forward reflection plane the full scan of the radiometer directly viewed the sun and the solar aureole as it scanned the upward hemisphere, which required that a lower gain of the radiometer be used to minimize saturation in the direction of the sun. As a consequence, the digitization steps of the reflection function at 0.75 μm are more apparent in this azimuth plane ($\phi = 0°$) than in the backscattering plane ($\phi = 180°$), where a higher gain of the radiometer was used, since the reflected and transmitted signal levels were much smaller in this plane. As a consequence, a greater resolution of the reflected intensity field was obtained in the $\phi = 180°$ plane than in the $\phi = 0°$ plane. Besides the rainbow and glory features previously described, Figure 2 shows that the reflection function of the smoke layer was nearly the same in the $\phi = 0°$ plane at both wavelengths, in contrast to the backscattering plane, where the smoke was about 20% brighter at 0.75 μm than at 1.64 μm.

3. Discussion and Conclusions

Could the cubic salt particles comprising much of the mass in the white smoke [*Ferek et al.*, this issue], the chain aggregates of spherical soot particles contained in the black smoke [*Johnson et al.*, 1991; *Weiss et al.*, this issue], or the large concentration of sulfate particles contained in both smokes and converted from SO_2 downwind of the fires [*Ferek et al.*, this issue], blend in such a way as to produce a gray smoke layer that scatters solar radiation as if it were composed of large spherical particles?

One of the few sets of measurements of the angular scattering matrix (including polarization) of nonspherical particles was obtained by *Perry et al.* [1978], who generated two types of nonspherical particles in the 0.1- to 1.0-μm size range by nebulizing saltwater solutions and drying the resulting droplets. These authors found that the rounded but not quite spherical particles of ammonium sulfate scattered radiation in a manner quite well described by Mie theory for spherical particles, whereas the cubic particles of sodium chloride differed substantially from light scattering by spherical particles. These discrepancies were especially pronounced in the backscattered direction that would have the greatest influence on the reflectance properties of the smoke that we observed. Furthermore, laboratory measurements of the angular scattering matrix of chain aggregates of one to four particles [*Bottiger et al.*, 1980] reveal increasing departures from spherical particle scattering as the scattering angle increases, being especially divergent in the backscattering direction.

Thus it appears that the rainbow and glory features that we observed in the polar reflectance pattern of the Kuwait oil-fire smoke could not have been produced by cubic salt particles or by chain aggregates of soot particles. As an alternative, we believe the likely explanation for these features is the presence of large oil-drizzle droplets generated downwind of the fires by condensation processes, as verified by examination of imagery from the Particle Measuring Systems, Inc. (PMS) two-dimensional cloud and precipitation probes aboard the aircraft within the first 100 km of the source region [*Hobbs and Radke*, 1992]. During this and other research flights we conducted during May and June, it was common to find dew point depressions of 20°C or more, with no corresponding indication of liquid water on the Johnson-Williams hot wire probe. Thus we reject the hypothesis that the rainbow and glory features that we observed could have arisen from liquid water droplets within the plume. Furthermore, our determination of the refractive index based on an analysis of the rainbow (oil bow) angle is consistent with the refractive index of various hydrocarbon compounds, such as benzene, octane, cyclohexane, cyclopentane, and decane, routinely found in oil. These compounds have refractive indices ranging between 1.39 and 1.45 [*Weast and Selby*, 1967].

The full analysis and interpretation of the measurements presented in Plate 1 and Figure 2 will require radiative transfer calculations to be performed for a wide variety of radiative properties of the smoke layer. It is only through these more extensive computations that we will be able to determine the single scattering albedo and optical thickness of the smoke layer required to match these measurements at each of the 13 wavelengths of the cloud absorption radiometer.

Acknowledgments. I am grateful to P. V. Hobbs of the University of Washington for inviting me to participate in this experiment and for directing the C-131A research flights, and to H. G. Meyer, G. T. Arnold, R. S. Fraser, S. C. Tsay, L. F. Radke, P. V. Hobbs, R. J. Ferek, and P. Pilewskie for useful comments and discussions. This work was supported by National Science Foundation grant ATM-9114993, National Geographic Society grant 10727-91, and the NASA Radiation Processes Research Program.

REFERENCES

Bakan, S., et al., Climate response to smoke from the burning oil wells in Kuwait, *Nature*, *351*, 367–371, 1991.

Bohren, C. F., and D. R. Huffman, *Absorption and Scattering of Light by Small Particles*, pp. 174–177, John Wiley, New York, 1983.

Bottiger, J. R., E. S. Fry, and R. C. Thompson, Phase matrix measurements for electromagnetic scattering by sphere aggregates, in *Light Scattering by Irregularly Shaped Particles*, edited by D. Schuerman, pp. 283–290, Plenum, New York, 1980.

Browning, K. A., et al., Environmental effects from burning oil wells in Kuwait, *Nature*, *351*, 363–367, 1991.

Cahalan, R. F., The Kuwait oil fires as seen by Landsat, *J. Geophys. Res.*, this issue.

Canby, T. Y., After the storm, *Natl. Geogr.*, *180*, 2–32, 1991.

Chandrasekhar, S., *Radiative Transfer*, 393 pp., Dover, New York, 1960.

Ferek, R. J., P. V. Hobbs, J. A. Herring, K. K. Laursen, R. E. Weiss, and R. A. Rasmussen, Chemical composition of emissions from the Kuwait oil fires, *J. Geophys. Res.*, this issue.

Hansen, J. E., Radiative transfer by doubling very thin layers, *Astrophys. J.*, *155*, 565–573, 1969.

Hansen, J. E., Multiple scattering of polarized light in planetary atmospheres, II, Sunlight reflected by terrestrial water clouds, *J. Atmos. Sci.*, *28*, 1400–1426, 1971.

Hobbs, P. V., and L. F. Radke, Airborne studies of the smoke from the Kuwait oil fires, *Science*, *256*, 987–991, 1992.

Johnson, D. W., C. G. Kilsby, D. S. McKenna, R. W. Saunders, G. J. Jenkins, F. B. Smith, and J. S. Foot, Airborne observations of the physical and chemical characteristics of the Kuwait oil smoke plume, *Nature*, *353*, 617–621, 1991.

King, M. D., M. G. Strange, P. Leone, and L. R. Blaine, Multiwavelength scanning radiometer for airborne measurements of scattered radiation within clouds, *J. Atmos. Oceanic Technol.*, *3*, 513–522, 1986.

Limaye, S. S., V. E. Suomi, C. Velden, and G. Tripoli, Satellite observations of smoke from oil fires in Kuwait, *Science*, *252*, 1536–1539, 1991.

Limaye, S. S., S. A. Ackerman, P. M. Fry, M. Isa, H. Ali, G. Ali, A. Wright, and A. Rangno, Satellite monitoring of smoke from the Kuwait oil fires, *J. Geophys. Res.*, this issue.

Perry, R. J., A. J. Hunt, and D. R. Huffman, Experimental determinations of Mueller scattering matrices for nonspherical particles, *Appl. Opt.*, *17*, 2700–2710, 1978.

Pilewskie, P., and F. P. J. Valero, Radiative effects of the smoke clouds from the Kuwait oil fires, *J. Geophys. Res.*, this issue.

Shannon, E. L., Jr., Testimony before the Gulf Pollution Task Force, Senate Environ. and Public Works Comm., July 11, 1991.

van de Hulst, H. C., *Multiple Light Scattering: Tables, Formulas, and Applications*, vol. 2, 437 pp., Academic, San Diego, Calif., 1980.

Weast, R. C., and S. M. Selby, *Handbook of Chemistry and Physics*, Chemical Rubber Company, Cleveland, Ohio, 1967.

Weiss, R. E., and P. V. Hobbs, Optical extinction properties of smoke from the Kuwait oil fires, *J. Geophys. Res.*, this issue.

Weiss, R. E., V. N. Kapustin, and P. V. Hobbs, Chain-aggregate aerosols in the smoke from the Kuwait oil fires, *J. Geophys. Res.*, this issue.

M. D. King, NASA Goddard Space Flight Center, Code 913, Greenbelt, MD 20771. (301) 286-5909; (301) 286-4804 (fax); king@climate.gsfc.nasa.gov (internet).

(Received December 10, 1991;
revised April 13, 1992;
accepted April 17, 1992.)