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B. J. Choudhury, T. Mo,
J. R. Wang and A. T. C. Chang

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National Aeronautics and
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Goddard Space Flight Center
Greenbelt, Maryland 20771

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B. J. Choudhury
Goddard Space Flight Center
Greenbelt, MD 20771

T. Mo
Computer Science Corporation
Silver Spring, MD 20910

J. R. Wang and A. T. C. Chang
Goddard Space Flight Center
Greenbelt, MD 20771

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GODDARD SPACE FLIGHT CENTER
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ABSTRACT

Impurities enter a snowpack as a result of fallout or scavenging by falling snow crystals. Albedo and flux extinction coefficient of soot contaminated snowcovers are studied using a two-stream approximation of the radiative transfer equation. The effect of soot is calculated by two methods: independent scattering by ice grains and impurities, and average refractive index for ice grains. Both methods predict a qualitatively similar effect of soot; the albedo is decreased and the extinction coefficient is increased compared to that for pure snow in the visible region; the infrared properties are largely unaffected. Quantitatively, however, the effect of soot is more pronounced in the average refractive index method. We find that soot contamination provides qualitative explanation for several snow observations.

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ALBEDO AND FLUX EXTINCTION COEFFICIENT OF IMPURE SNOW FOR DIFFUSE SHORTWAVE RADIATION

Albedo and flux extinction coefficient, which are basic shortwave radiative properties of snow, are known to be highly variable. For deep snowcovers observed albedo ranges from 65 to 96 percent and extinction coefficient from 0.07 to 0.17 cm^{-1} in the blue-green (0.45 μm) region of the solar flux (Thomas, 1963; Kondratiev et al., 1964; Grenfell and Maykut, 1977; Mellor, 1977). Recent radiative transfer studies (Choudhury, 1981; Wiscombe and Warren, 1980) could not explain such variability for pure snow. Since attempts are being made to correlate changes in albedo and microwave brightness temperature with snowpack physical characteristics (McGinnis, 1975; Foster et al., 1980), it is important to understand this variability.

Natural snowcovers are expected to contain some impurities. Soot, released into the atmosphere due to fossil fuel burning, can enter snowpacks by fallout or as a result of scavenging by falling snow crystals. The absorption coefficient of soot is more than five and eight orders of magnitude higher than pure ice in, respectively, microwave and visible regions (Bartky, 1968). A small concentration of soot can therefore affect visible and microwave observations. Although soot is not the only impurity that can be present in a snowcover, this report gives quantitative results for soot only, because of its high absorptivity.

Multiple scattering within the snowpack is studied by a two-stream approximation, for which Choudhury and Chang (1979) and Grenfell and Maykut (1977) have given equations for albedo and flux extinction coefficient. The scattering parameters (cross-sections and the asymmetry factor for phase function) needed for the calculation of these radiative properties depend upon size and refractive index of scattering particles. For impure snow, consisting of particles (ice grains and impurities) with differing refractive indices, the scattering parameters can be calculated by two methods (Bartky, 1968; Lindberg, 1975; Gillespie et al., 1978; Warren and Wiscombe, 1980): (1) calculate separately the scattering parameters for ice grains and impurities and aver-

age by corresponding number fractions, and (2) use fractional volumes of ice and impurity to calculate an average refractive index for all particles. These methods, referred below as isolated particle and average refractive index models, may represent physical situations when the impurities are unattached or attached to the ice grains. Certainly, these two situations can co-exist within a snowcover. A recent study by Warren and Wiscombe (1980) is based on the isolated particle model, and they used a different radiative transfer solution.

The scattering parameters are calculated using geometrical optics formulae (Choudhury and Chang, 1981) for ice grains and Mie scattering theory (Hansen and Travis, 1974) for soot particles. We assumed all ice grains are of equal size, and used a modified-gamma size distribution for soot particles (Bartky, 1968). The refractive indices are from Hobbs (1974) for ice and from Dalzell and Sarofim (1969) for propane soot. The soot parameters were chosen slightly different by Warren and Wiscombe (1980). We note that the characteristics of the impurity will depend largely upon its source.

Albedo of pure and soot contaminated snow are shown in Figure 1. Soot in amounts of a few parts per million by weight (ppmw) can reduce visible albedo by several percent without affecting near infrared albedo. It is also seen that although isolated particle and average refractive index models predict similar effects of soot, this effect is more pronounced in the average refractive index model. It is difficult to clarify in physical terms the cause of this difference between the models since they use different methods for calculating the scattering parameters. However, if these models are representing the physical situations discussed previously, this difference indicates that the impurities imbedded or attached to the ice grains are more effective in changing the albedo than the isolated impurities. For a given weight fraction of soot, the corresponding volume fraction increases as the ice grain size increases. Thus for same weight fraction, soot will affect the visible albedo of coarse grained snow more than fine grained snow. If new snow is contaminated (e.g., due to scavenging) then with aging the visible albedo will decrease

rapidly due not only to increasing grain size but also increasing volume fraction of impurity. These considerations are pertinent in remote sensing when snow depth is to be correlated with visible albedo.

Comparison with observations (Grenfell, 1981) is shown in Figure 2. The ice grain radius of 0.2mm, used in this comparison, is slightly larger than the observed 0.1 to 0.15mm. Although by varying the amount of soot the visible albedo can be matched using the observed grain radius, the near infrared albedo will be predicted a few percent higher. This discrepancy with respect to grain size indicates some deficiencies in the two-stream radiative transfer model of snow. One should, however, note that near infrared albedos are affected primarily by the ice grains in the surface centimeter layer. If these grains are slightly larger that the observed values (due to nonuniform metamorphism) then this discrepancy will not arise. The grain profile information is not given in Grenfell (1981) to further analyze this possibility.

Bohren and Barkstrom (1974) showed that the albedo is directly proportional to the square root of grain size. We calculated integrated albedos for varied grain size and soot content, and found such a relationship. For the average refractive index model, the intercept (C_1) and slope (C_2) of this relationship, $A = C_1 - C_2 r^{1/2}$ (where r is grain radius in mm), are given in Table 1. This parameterized equation may be helpful in climatology and hydrology for energy balance calculations.

In Figure 2 a fairly good agreement between observed and calculated albedos is shown. A crucial model validation, however, is in matching both albedos and flux extinction coefficients, when they have been observed concurrently. The reason being they provide complementary radiative transfer information dependent on the same parameters. One should, however, note that the extinction coefficient depends more strongly on grain size and absorption coefficients of ice and impurity than does albedo. An attempt to match such observations by Grenfell and Maykut (1977) is shown in Figure 3. An ice grain radius of 0.1mm seems more appropriate for matching the albedos because for this radius the predicted albedos agree better with observations beyond

0.95μm – a region not affected by soot. With this grain radius if we adjust the soot content so as to match the visible albedo, we find that the predicted extinction coefficients disagree by more than a factor of two. It is also seen that matching of extinction coefficients was not very successful. The weakness of the model and/or inaccuracies of input parameters (both soot and ice) to represent these observations are clear. Warren and Wiscombe (1980) matched these albedos but did not compare with extinction coefficients. In matching the albedo observations of Kuhn and Siogas (1978), Warren and Wiscombe used 1.5 ppmw of soot with ice grain radius 0.1 mm. For these soot and ice parameters we find that calculated extinction coefficients are an order of magnitude higher than the observations. In fact the extinction coefficients observed by Kuhn and Siogas are what may be expected for pure snow (Choudhury, 1981). It is possible that these discrepancies are partly due to observational error (M. Kuhn, private communication) and partly due to assumed impurity characteristics, but until explained, the model predictions should be treated cautiously. Our results, however, substantiate the importance of impurity contamination (Dunkle and Bevans, 1956; Warren and Wiscombe, 1980) in understanding the radiative properties of natural snowpacks.

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Table 1
Intercept and slope of parameterized equation for integrated albedo:
$A = C_1 - C_2 r^{1/2}$; r in mm.

Soot (ppmw)	Intercept	Slope
0.0	0.960	0.153
0.05	0.960	0.191
0.10	0.961	0.214
0.50	0.960	0.313
1.0	0.958	0.382

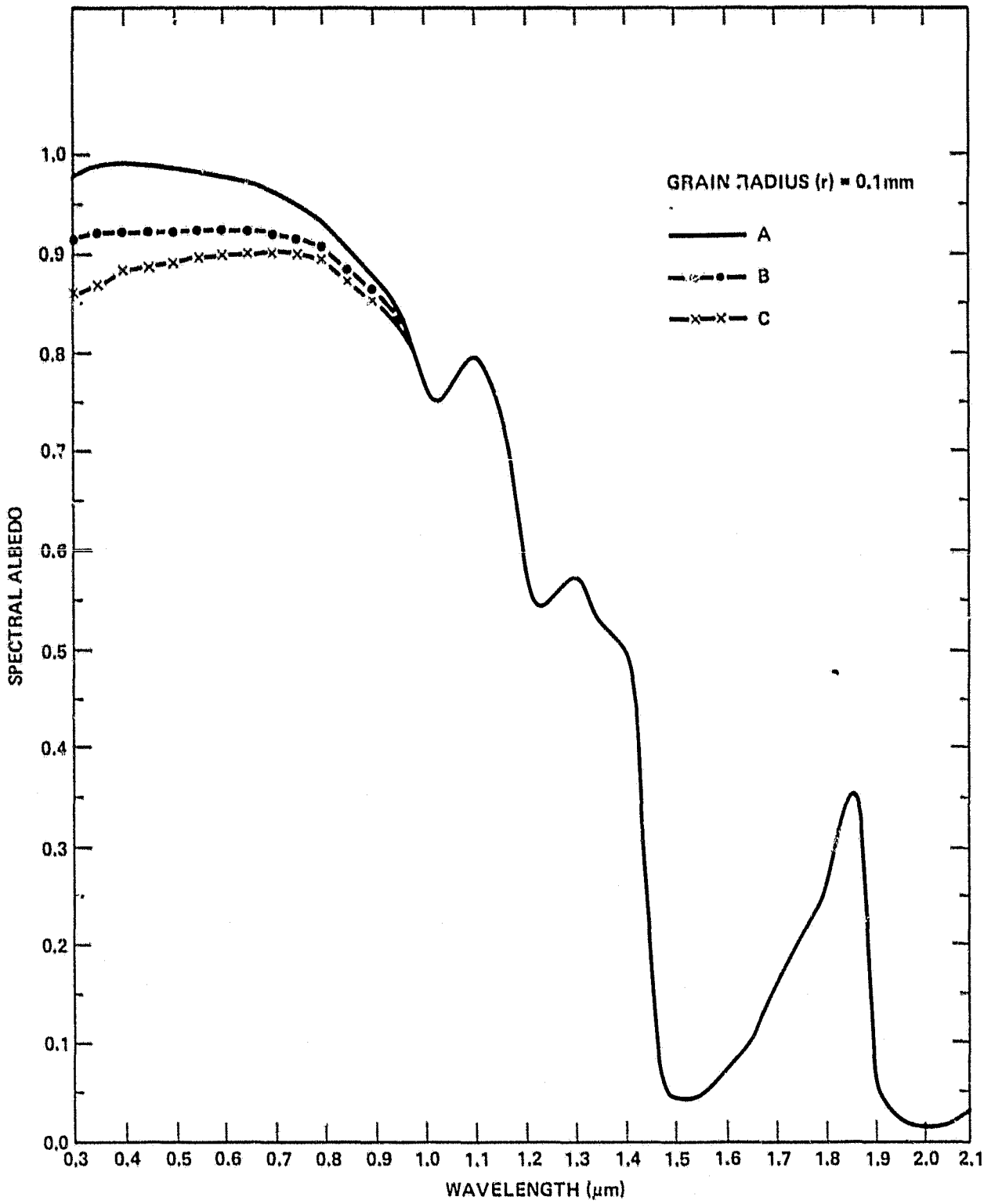

Figure 1. Effect of 1.0 ppmw of soot on albedo of snow with grain radius 0.1 mm. (A) pure snow, (B) isolated particle model, (C) average refractive index model. For the same amount of soot note the difference between (B) and (C).

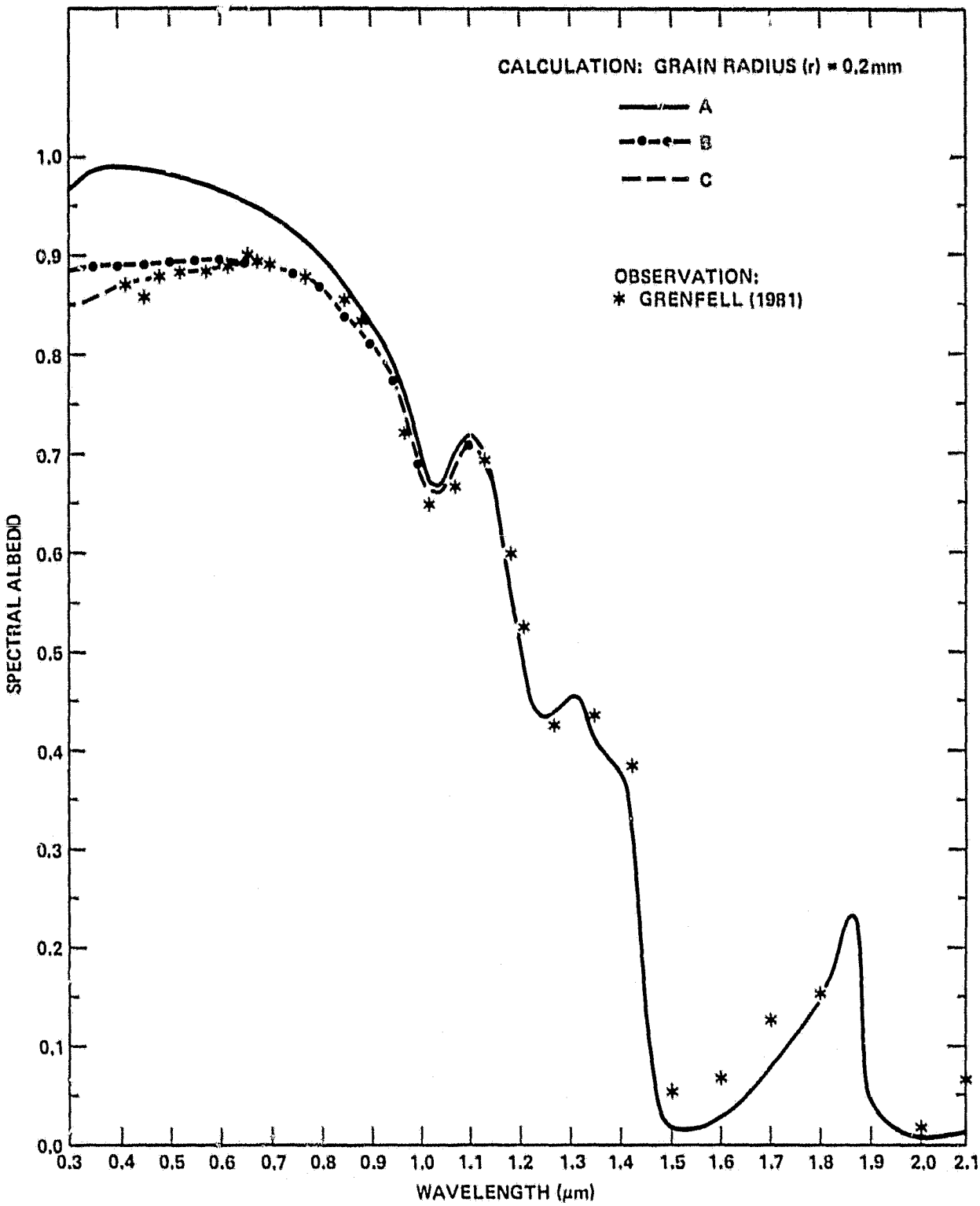

Figure 2. Comparison of calculated albedo with observations (Grenfell, 1981). (A) pure snow, (B) isolated particle model with 1.0 ppmw of soot, (C) average refractive index model with 0.5 ppmw of soot. Note the difference in the amount of soot for (B) and (C).

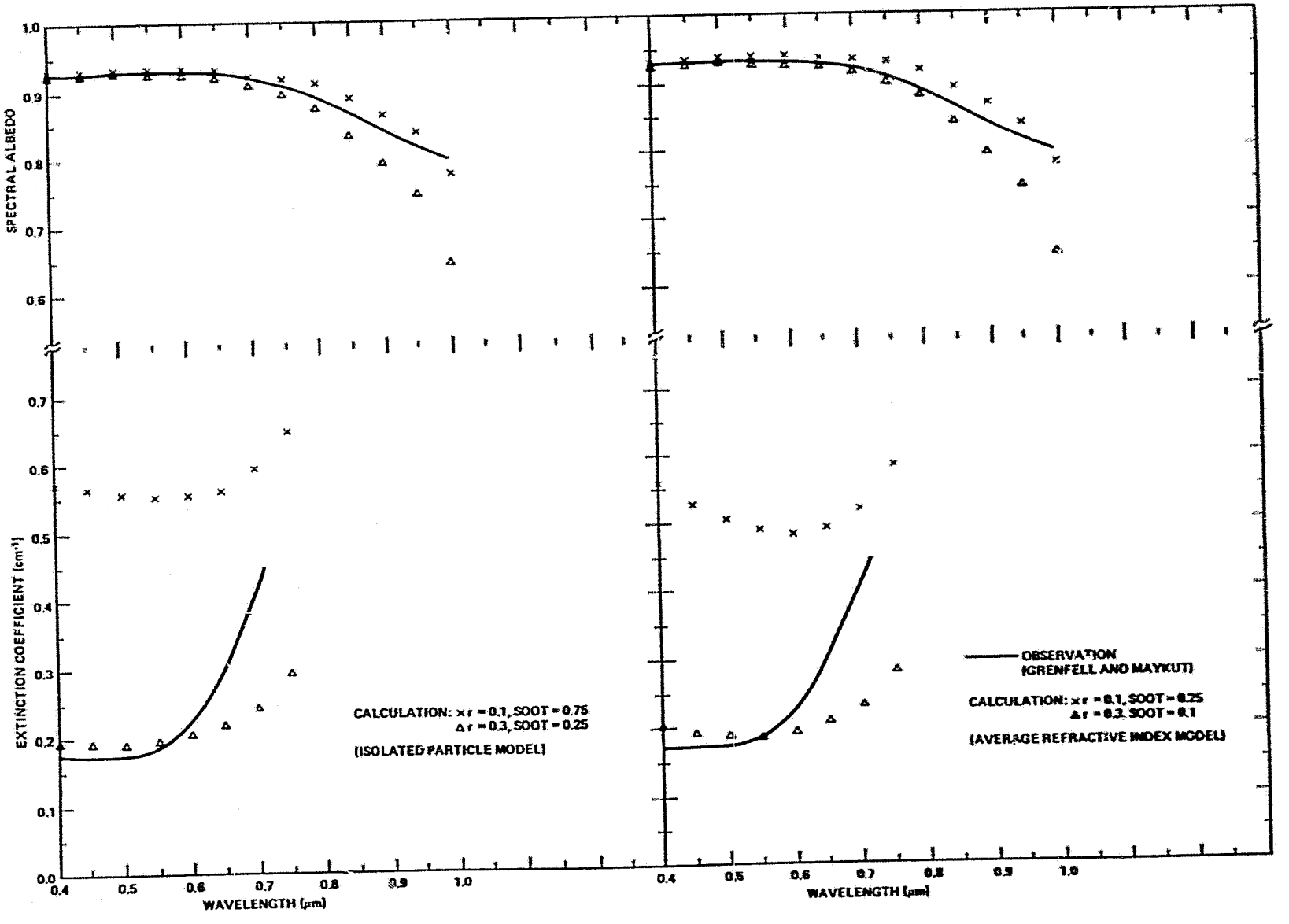

Figure 3. Comparison of flux extinction coefficient and albedo with observations (Grenfell and Maykut, 1977). Results from isolated particle and average refractive index models are shown side-by-side. Note the difference in soot content for these results and the sensitivity of extinction coefficient with respect to ice and soot parameters in the visible region.

Figure Captions

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