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DEPENDENCE OF RADIATIVE PROPERTIES OF ARCTIC STRATUS CLOUDS ON CLOUD MICROSTRUCTURE

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Abstract. Observations of cloud microstructure during the Beaufort Sea Arctic Stratus Cloud Experiments of June 1980 showed that the drop size distributions typically are nonuniform changing from monomodal near the base to bimodal near the top of the cloud. The observed drop size distributions are used to compute the reflection and transmission of solar radiation by Arctic Stratus Clouds in the visible part of the spectrum. Solutions of the radiative transfer equation using three different vertically uniform drop size distributions closely resembling those observed near the bottom, middle and top of the cloud, respectively, resulted in significant changes in the radiative properties even though the column liquid water content is kept constant. This finding implies that the shortwave optical depth of Arctic Stratus Clouds cannot be related to the column liquid water content (inferred from longwave satellite radiometry) unless realistic height-varying drop size distributions are used. It also implies that in order to make reliable predictions concerning the clouds' effect on the surface heat balance, one needs not only the column liquid water content but also height profiles of the drop size distributions.

Introduction

Arctic Stratus Clouds play a dominant role in determining the surface heat balance during the Arctic summer (e.g., Vowinckel and Orwig, 1970; Herman, 1977, 1980; and Herman and Goody, 1976). An assessment of the surface heat balance is crucial for determining the melting rate of the surface pack ice and requires an understanding of the radiative properties of the Arctic Stratus Clouds which in turn depend on their cloud microstructure. The purpose of the present letter is to emphasize one important aspect of these observations: namely that the nonuniform nature of the observed drop size distributions must be taken into account in model calculations aimed at predicting the radiative properties of these clouds.

Radiation Model

Our model calculations are based on the discrete ordinate approximation to the radiative transfer equation developed by Stamnes and Swanson (1981) and extended upon for application to inhomogeneous atmospheres by Stamnes and Conklin (1983). The plane-parallel geometry is adequate because the clouds showed remarkable horizontal homogeneity. For the point we want to make in this letter it is sufficient to focus on the visible part of the spectrum between 0.3 μm and 0.7 μm in which atmospheric absorption is negligible (Lacis and Hansen, 1974).

If we assume that the clouds consist of pure-water drops the scattering will be conservative with a single scattering albedo equal to unity. Additional physical parameters needed for our model are the scattering phase function and the cloud optical depth which can be obtained from the observed drop size distributions. Hansen (1969) and van de Hulst (1970) have shown that to determine the radiative properties of clouds only the first moment of the phase function, commonly referred to as the asymmetry factor, is important. Thus, in the present calculations we have utilized the Henyey-Greenstein phase function which depends only on the asymmetry factor to circumvent time-consuming computations of phase functions and their moments. Twomey (1976) found that the asymmetry factor varies only slightly for most terrestrial clouds and ranges from 0.82 to 0.86 for lower-level clouds and Herman (1977) estimated a constant value near 0.85 Arctic Stratus Clouds. Test calculations using 0.82 and 0.86 yielded a deviation of less than 1% in the reflectivity showing that the results are not very sensitive to the value used for the asymmetry factor.

The cloud optical depth at wavelength λ, $\tau_c(\lambda)$ is calculated from the detailed vertical profiles of the droplet size distribution by summing over altitude and drop sizes as follows:

$$\tau_c(\lambda) = \sum_{i=1}^{p} \sum_{j=1}^{m} n(D_j, Z_i)\, \sigma_{ext}(X_j)\, (\Delta Z)_i \qquad (1)$$

where D_j is the diameter, X_j is the size parameter ($X_j = \pi D_j/\lambda$), Z_i the altitude, $n(D_j, Z_i)$ the number density of droplets at altitude Z_i with diameter D_j, and $\sigma_{ext}(X_j)$ the extinction cross section. Our calculations showed that the optical depth varies only slightly (less than 1%) for wavelengths between 0.3 and 0.7 μm and can be represented by its value at 0.5 μm.

Results

In an attempt to compare our model predictions with the observations we show in Table 1 reflectivity and transmissivity for the nearly plane-parallel clouds observed on June 20 and June 28.

The measured values were provided by Dr. G. Herman of the University of Wisconsin who was in charge of the radiation measurements of the Beaufort Sea experiments. They were deduced from

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TABLE 1. Computed and Measured Reflectivities (R) and Transmissivities (T)

		Measured	Computed	
		Dr. G. Herman	Slingo and Schrecker Model	Present Model
June 20	R(%)	65.6 ± 0.9	73.7	74.6
	T(%)	64.5 ± 1.6	65.7	63.0
June 28	R(%)	78.9 ± 1.1	84.5	84.4
	T(%)	53.9 ± 1.0	52.1	46.7

the difference in the upward and downward fluxes between total solar spectrum (0.28 - 4.0 μm) and the near infrared (0.78 - 4.0 μm). The range of uncertainty in these values represent the standard error in the mean arising from horizontal inhomogeneities and do not refer to instrumental accuracy. Radiative properties were measured using Eppley pyramometers and Silicon flux detectors. The measured values were consistent to within 10%.

The computed values are those from our model and that of Slingo and Schrecker model computed by Dr. Herman using the Delta-Eddington approximation (Joseph et al., 1976; Wiscombe, 1977). Both calculations used the solar zenith angle and surface albedo appropriate for the experimental situation. The measured and computed values agree to within 10% which support the validity of the two radiation models. Since our model yields essentially exact results for given input data the small discrepancy between the two models is probably due to the approximate solution (the Delta-Eddington approach) to the radiative transfer equation. The measured radiative fluxes imply significant absorption, we therefore feel that the agreement between our model and the observations is perhaps as good as one should expect.

In our model the reflectivity and transmissivity depend only on the total optical depth (ignoring the very weak dependence on asymmetry factor) which for specified column liquid water content is determined by the drop size distribution. Figure 1 shows the measured drop size distribuions for the cloud of June 28. We note that the drop size distribution changes from a single mode near the cloud base to a double mode near the cloud top. In order to assess the importance of using the correct altitude-dependent drop size distribution we computed the reflectivity and transmissivity for three different vertically uniform drop size distributions closely resembling those observed near the base (Model I), middle (Model II) and top (Model III) of the cloud. These hypothetical distributions, all constrained to yield the observed column liquid water content of 125.5 g/m^2, are shown in Figure 2. The mean concentration, mean drop size and optical depths for the three models are compared with the observed values in Table 2. The asymmetry factor was adopted to be 0.82 for Model I, 0.84 for Model II and 0.86 for Model III to reflect the different mean drop sizes in the models (cf. Table 2).

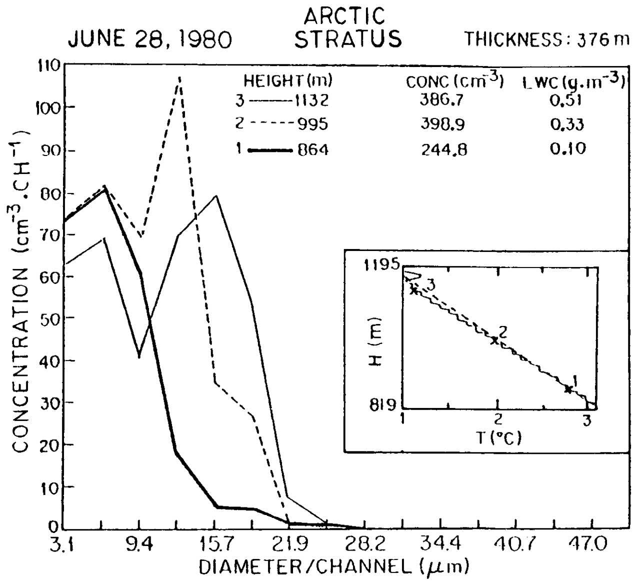

Fig. 1. Drop size distribution measured at three different heights for the stratus cloud observed on June 28, 1980. The diameter shown in the mean value for each channel of the forward scattering spectrometer probe.

The reflectivities and transmissivities resulting from the three different models are compared to those obtained from the observed drop size distributions of June 28 cloud (see Figure 1) and shown in Figure 3. We note that Model I and II overestimate the reflectivity and underestimate the transmissivity while the reverse is true for Model III. This result is consistent with the optical depth values given in Table 2. Comparing the computed radiative properties of the model clouds with those of the actual cloud (Figure 3) we find that the deviations in reflec-

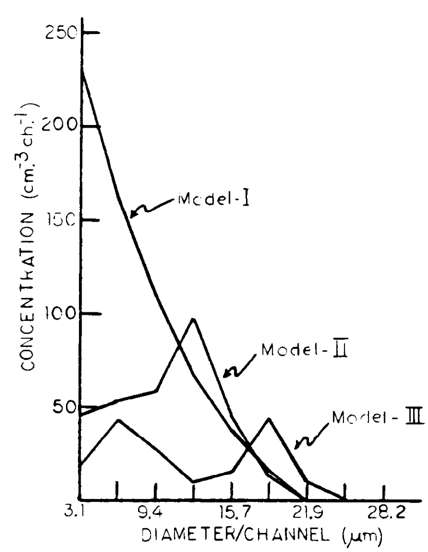

Fig. 2. Three models of drop size distributions constrained to have the same liquid water content.

tivity range from an increase of 7% (Model I) to a decrease of 6% (Model III) whereas the corresponding deviations in transmissivity range from a decrease of 23% (Model I) to an increase of 21% (Model III). Figure 3 also shows that the Model II cloud which assumes a normal drop size distribution, yields results closest to those obtained from the observed drop size distribution. This finding could perhaps have been anticipated from Figure 1 which indicates that an "average" drop size distribution for the cloud is likely to agree better with Model II than either of Model I and III.

The computations presented in Figure 3 are based on the assumption that the underlying ground is a Lambert reflector. The average surface albedos for various surface conditions obtained by Chernigovskiy (1963) from floating ice stations in the summertime Arctic Ocean are indicated in Figure 3. It is evident from Figure 3 that transmissivity is dependent heavily on ground albedo while the reflectivity is only weakly affected.

Many aerosol measurements in recent years have documented the existence of a diffuse haze layer in the Arctic atmosphere (Rahn and McCaffrey, 1980; Rahn, 1981). The relatively absorbing nature of the aerosol implies that the haze may have a heating effect, and there have been several studies (e.g., Shaw and Stamnes, 1980; Porch and MacCracken, 1982) indicating that the effects may be significant. A recent study of the radiative properties of the Arctic aerosol (Patterson et al., 1982) yielded a single scattering albedo between 0.8 and 0.9 and an asymmetry factor of 0.68.

In order to assess the possible impact of the aerosol in connection with Arctic Stratus Clouds we added a hypothetical source of aerosol to the cloud. We assumed for simplicity that the aerosol particles were uniformly mixed with the cloud droplets. While this assumption will give unrealistic results for heating rate profiles, it will not significantly affect the bulk absorptivity of the cloud which we are interested in here (Stamnes, 1982). Absorptivity was calculated for two cases in which the aerosol single scattering albedo and optical depth were (1) 0.8 and 0.2, respectively, (2) 0.9 and 0.1, respectively. Case (1) refers to a possible worst scenario which is probably more appropriate for strong aerosol injections occurring during the Arctic winter and spring when Arctic Stratus Clouds are less likely to be present. Case (2) could conceivably be associated with aerosol episodes during the Arctic summer. Computations show that absorptivities due to Arctic haze imbedded in Arctic Stratus may range from 1-3% to 7-10% (worst case) depending on surface conditions. The drop size distribution has an effect on the absorptivity but only for the worst hypothetical case and for high surface albedo.

TABLE 2. Parameters Describing the Three Models of Drop Size Distributions Shown in Figure 2

	mean conc.	mean size	optical depth	asymmetry factor
Model-I	622 cm^{-3}	7.24 μm	31.36	0.82
Model-II	312 cm^{-3}	10.33 μm	28.06	0.84
Model-III	174 cm^{-3}	11.84 μm	22.27	0.86
Observed	234 cm^{-3}	9.98 μm	25.35	0.84

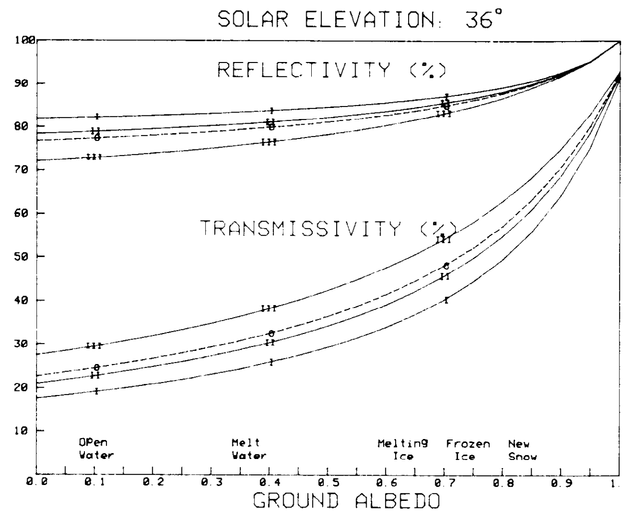

Fig. 3. Computed reflectivities and transmissivities for three model clouds and the observed cloud.

Conclusion

A radiative transfer model has been used to examine the dependence of radiative properties of Arctic Stratus Clouds on cloud microstructure. Comparing reflectivities and transmissivities in the visible part of the spectrum based on three different uniform models of the drop size distribution (closely resembling those observed near the base (Model I), middle (Model II) and top (Model III) of the cloud) with those obtained by using the observed nonuniform distributions we have found deviations in reflectivity ranging from an increase of 7% (Model I) to a decrease of 6% (Model III) and corresponding deviations in transmissivity ranging from a decrease of 23% (Model I) to an increase of 21% (Model III). The column liquid water content was constrained to equal the observed value in the three models. These results suggest that care must be exercised when relating shortwave optical depth to cloud column liquid water content (Stephens, 1978) obtained from longwave satellite radiometry (Grody, 1976), and that the surface heat balance responds sensitively to changes in the drop size distribution of the cloud.

Absorptivity in clouds is not sensitive to drop size distirbution except in the case where the single scattering albedo of haze is near or less than 0.8 and when the surface has a high albedo.

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References

Chernigovskiy, N. T., Radiational properties of the central Arctic Ice Coast, Eng. Trans. Rand Mem. RM-5003-PR, 151-173, 1963.

Grody, N. C., Remote sensing of atmospheric water content from satellite using microwave radiometry, IEEE Trans. Antennas Propagat., 24, 155-162, 1976.

Hanson, J. E., Exact and approximate solutions for multiple scattering by cloudy and hazy planetary atmospheres, J. Atmos. Sci., 26, 478-487, 1969.

Herman, G. F., and R. Goody, Formation and persistence of summertime Arctic Stratus Clouds, J. Atmos. Sci., 33, 1537-1553, 1976.

Herman, G. F., Solar radiation in summertime Arctic Stratus Clouds, J. Atmos. Sci., 34, 1423-1432, 1977.

Herman, G. F., Thermal radiation in Arctic Stratus Clouds, Quart. J. R. Met. Soc., 106, 771-780, 1980.

Joseph, J. H., W. J. Wiscombe, and J. A. Weinman, The Delta-Edditngton approximation for computations of the solar radiation budget in a cloudy atmosphere, J. Atmos. Sci., 35, 2452-2459, 1976.

Lacis, A. A., and J. E. Hansen, A parameterization for the absorption of solar radiation in the earth's atmosphere, J. Atmos. Sci., 31, 118-133, 1974.

Patterson, E. M., B. T. Marshall, and K. A. Rahn, Radiative properties of the arctic aerosol, Atmospheric Environment, 16, 2967-2977, 1982.

Porch, W. M., and M. C. MacCracken, Parametric study of the effects of Arctic soot on solar radiation, Atmospheric Environment, 16, 1365-1371, 1982.

Rahn, K. A., and R. J. McCaffrey, On the origin and transport of the winter Arctic aerosol, Ann N.Y. Acad. Sci., 338, 486-503, 1980.

Rahn, K. A., Relative importance of North America and Eurasia as sources of Arctic aerosol, Atmospheric Environment, 15, 1447-1455, 1981.

Shaw, G. E., and K. Stamnes, Arctic haze: perturbation of the polar radiation budget, Ann. N.Y. Acad. Sci., 338, 533-539, 1980.

Slingo, A., and H. M. Schrecker, On the shortwave radiative properties of stratiform water clouds, Quart. J. R. Met. Soc., 108, 407-426, 1982.

Stamnes, K., and R. A. Swanson, A new look of the discrete ordinate method for radiative transfer calculations in anisotropically scattering atmospheres, J. Atmos. Sci., 38, 387-399, 1981.

Stamnes, K., Reflection and transmission by a vertically inhomogeneous planetary atmosphere, Planet. Space Sci., 30, 727-732, 1982.

Stamnes, K., and P. Conklin, A new multi-layer discrete ordinate approach to radiative transfer in vertically inhomogeneous atmospheres, J. Quant. Spectrosc. Radiat. Transfer, in press, 1983.

Stephens, G. L., Radiation profiles in extended water clouds. II: Parameterization schemes, J. Atmos. Sci., 35, 2123-2132, 1978.

Twomey, S., Computations of the absorption of solar radiation by clouds, J. Atmos. Sci., 33, 1087-1091, 1976.

van de Hulst, H. C., Some problems of anisotropic scattering in planetary atmospheres, Planetary Atmospheres, C. Sagan et al., eds., Reidel, 177-185, 1970.

Vowinckel, E., and S. Orvig, The climate of the north polar basin, World Survey of Climatology, 14, 129-225, 1970.

Wiscombe, W.J., The Delta-Eddington approximation for a vertically inhomogeneous atmosphere, NCAR Technical Note, TN-121+STR, 1977.

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