8.4 CLOUDS OVER SEA ICE AND OPEN WATER IN THE SOUTHERN OCEAN: SOLAR TRANSMITTANCE AND CLOUD RADIATIVE FORCING FROM SHIPBOARD MEASUREMENTS

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1. INTRODUCTION

The latitude zone 55-70°S is the cloudiest on Earth. Because of their great areal coverage, the properties of clouds in this region are important for understanding the radiation budget of the sea ice and the Southern Ocean. Lack of knowledge of cloud distributions and cloud properties, and the behaviour of clouds during climatic change, limits the accuracy of climate-prediction models. Cloud distributions and radiative properties are now being monitored by satellite; however, there is also a need for surface measurements of cloud properties. Routine solar radiation measurements, which can be used to determine the cloud radiative forcing (CRF) at the surface, are made at weather stations worldwide, and on many research ships, using broadband pyranometers. Here we investigate what information about clouds can be obtained from broadband measurements, with particular attention to the effect of surface albedo on the measured downward shortwave irradiance. A parameterization, relating cloud transmittance to optical depth, surface albedo and solar zenith angle, is developed. It is applied to pyranometer measurements from ship observations in the Antarctic sea-ice zone and the Southern Ocean.

2. VOYAGE DATA

Some cloud radiative properties can be determined simply using *in situ* measurements from the many voyages occurring in the Southern Ocean. For this study, measurements were made on a springtime voyage of *RSV Aurora Australis* between Tasmania and East Antarctica, 47-69°S in 1996. The ship's permanent equipment includes two gimballed broadband pyranometers (0.3-2.8 μm) on opposite sides of the ship that are cleaned daily by a technician. Comparison of the two pyranometers allows testing for errors due to shadowing and tilt. Surface albedo is obtained from hourly visual observations of fractional areas of ice types taken throughout the two-month voyage from September to November, together with measured albedos of each ice type. Typical values of surface albedo, which show great variability within the sea-ice zone, are given in Figure 1.

Our method for obtaining cloud properties makes use of methods developed by Leontyeva and Stamnes (1994) and Lubin and Simpson (1997); it differs from theirs in that we do not compute the clear-sky transmittance using a radiative transfer model, but rather by observation. Clear-sky transmittances are obtained as a function of solar zenith angle for several clear days. We define raw cloud transmittance (*trc*) as the ratio of downward irradiance under cloud to that under clear sky at the same solar zenith angle (θ). Clear sky is much more common over the sea ice. In the sea-ice zone *trc* under cloud is greater principally because of multiple reflections over the higher surface albedo (α). The reduction in downward shortwave irradiance relative to clear sky we call "downward shortwave cloud radiative forcing", CRF_d, which is plotted in Figure 2 versus solar zenith angle. The more frequent occurrence of clear sky over sea ice than over open ocean is apparent. The net shortwave cloud radiative forcing (CRF_n), shown in Figure 3, is obtained by multiplying CRF_d by (1- α). CRF_n is smaller over sea ice due to both the higher surface albedo and the less-frequent occurrence of clouds. Each average (for a solar-zenith-angle bin) is the difference in net shortwave irradiance between all conditions and clear conditions.

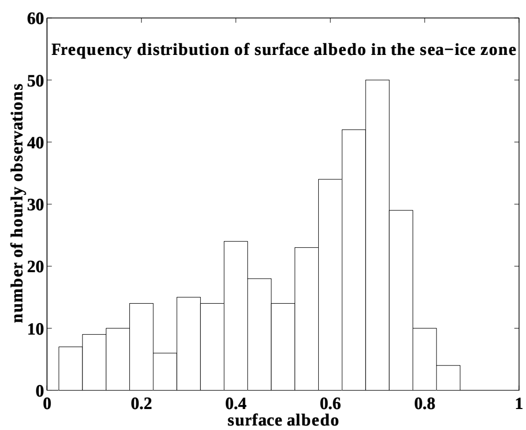

Figure 1: Surface albedo in the sea-ice zone

3. PARAMETERIZATION

In order that the isolated surface measurements of CRF can be extended to larger areas using a cloud climatology (e.g. Warren et al. 1988), inherent cloud radiative properties are needed. A value for cloud transmittance can be obtained as discussed above. However, this same cloud would have a different measured transmittance if illuminated at a different zenith angle θ or if positioned over a surface with different albedo α. To use a cloud climatology to compute surface CRF therefore requires an intermediate quantity that is inherent to the cloud field (which may be inhomogeneous and non-overcast),

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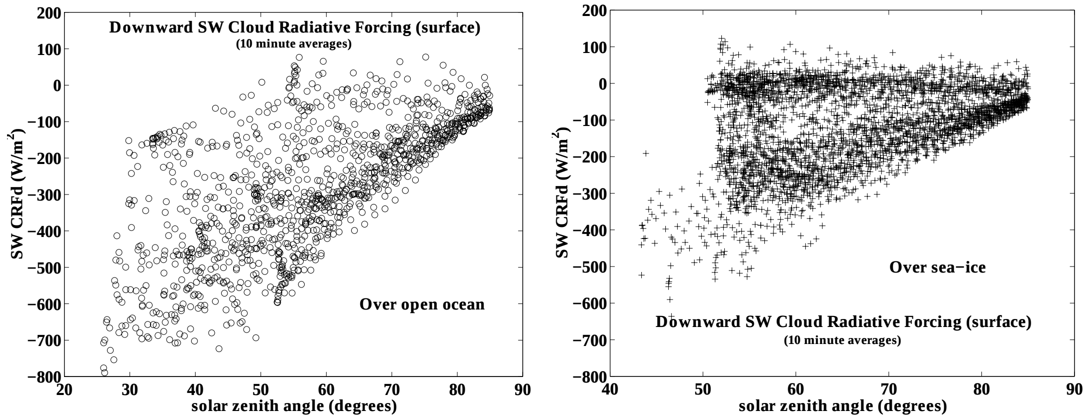

Figure 2. Ten minute averages of the downward shortwave cloud radiative forcing as a function of solar zenith angle. (a) Over open ocean. (b) Over sea ice.

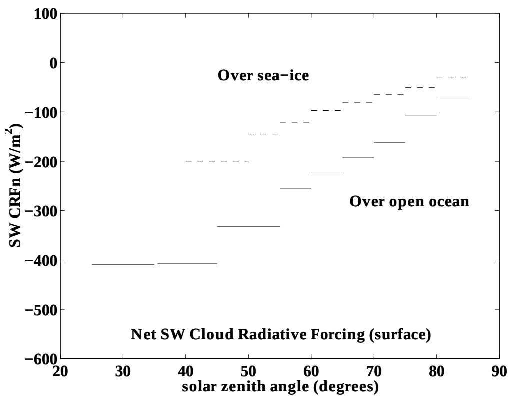

Figure 3. Net shortwave cloud radiative forcing, averaged over bins of solar zenith angle.

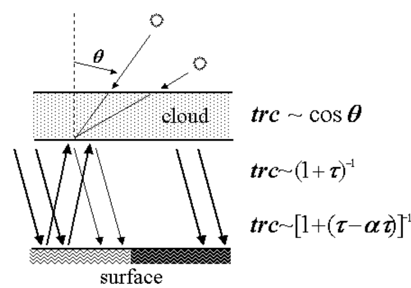

Figure 4: Schematic of the physical basis of the parameterization

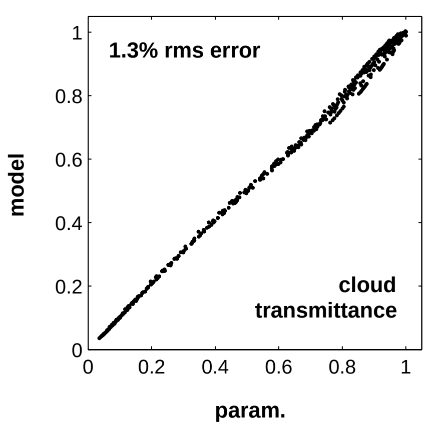

Figure 5: Comparison of model and parameterization

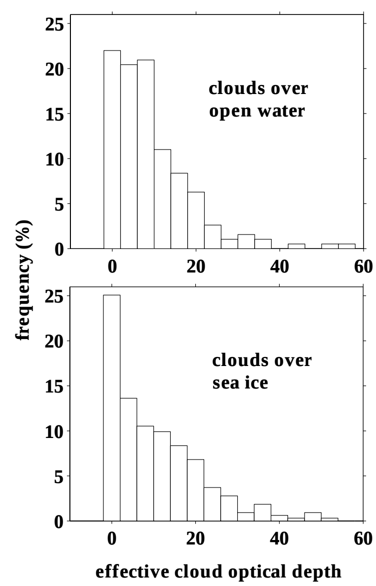

Figure 6: Cloud optical depth in the Southern Ocean

which can be used to compute transmittance given θ and α. This intermediate quantity is the effective optical depth τ. It is “effective" in two senses: (a) it is computed assuming a horizontally homogeneous overcast cloud, and (b) the cloud is assumed to consist of liquid water droplets with a standard effective radius. Wiscombe (1975) motivated the form of a parameterization for Arctic summer stratus clouds, relating cloud transmittance to cloud droplet number density for a grey underlying surface. We have re-derived this parameterization using a spectrally-varying surface albedo and several cloud drop-size distributions (described by an effective radius *reff*). Figure 4 shows a schematic diagram of the physical basis of the parameterization. The measured raw cloud transmittance, *trc,* is (i) proportional to the cosine of the solar zenith angle θ (ii) inversely proportional to cloud optical depth τ, and (iii) increased by multiple reflection between the cloud base and the surface with albedo α.

Our parameterization is

$$trc = \frac{a(\tau) + b(\tau)\cos\theta}{1 + (c - d\alpha)\tau} \qquad (1)$$

where

$$a(\tau) = a_1 + (1 - a_1)\exp(-k_1\tau) \qquad (2)$$

and

$$b(\tau) = b_1\left[1 + b_2\exp(-k_2\tau) + b_3\exp(-k_3\tau)\right] \qquad (3)$$

The coefficients *a, b, c,* and *d* were determined using a non-linear least-squares algorithm, separately for each of three different drop-size distributions, covering a range of solar zenith angles, surface albedos and cloud optical depths. Values of the coefficients in this broadband parameterization are available at the URL below. In Figure 5, cloud transmittance values derived using the parameterization for a cloud drop-size distribution typical of the Southern Ocean (*reff*=8.6 μm) show an rms error of 1.3% when compared to transmittance computed by the model.

4. APPLICATION TO MEASUREMENTS

The broadband parameterization is applied to measurements of *trc*, α, and θ made in the East Antarctic sea-ice zone: Figure 6 shows effective cloud optical depth τ over the sea-ice (defined as concentration of sea ice > two tenths) and over the open water. However, for climatological applications, τ is simply an intermediate quantity that allows us to find the transmittance of the same cloud field over different surfaces and at different solar zenith angles. In Figure 7, we explain how this is done, taking into account the lack of knowledge of the actual drop-size distribution in clouds. In this example a cloud was observed over a surface of albedo 0.1, and the measured transmittance of solar radiation *trc* was 0.35. If we assume *reff*= 8.6μm we obtain a τ of 13.8. We estimate using the parameterization that if this cloud were placed over a surface of albedo 0.6, it would have a *trc* of 0.528. If we instead had larger drops (*reff*=20μm) we infer a τ of 15.2, and estimate that if this cloud were placed over the high-albedo surface it would have a *trc* of 0.512, very close to that estimated using the smaller drops. Thus, lack of knowledge of cloud drop-size distribution can cause errors of 10-15% in the intermediate quantity τ but only 2% in the prediction of solar transmittance in another environment.

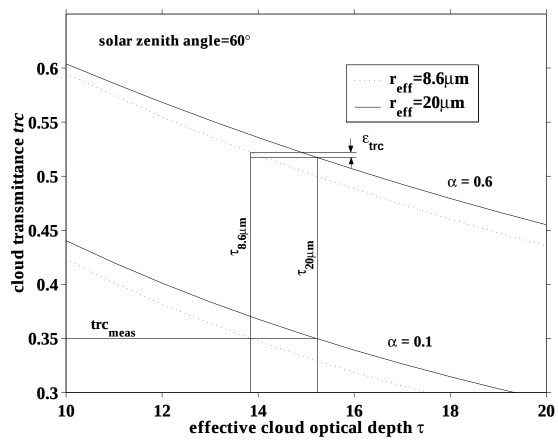

Figure 7: Errors due to lack of knowledge of cloud drop-size distribution

The parameterization is intended for use in the analysis of measured surface irradiance to obtain an effective cloud optical depth τ from measurements of *trc*. The inferred value of τ is an inherent property of the cloud field, allowing both the computation of cloud transmittance for other conditions of solar illumination and surface albedo, and the use of instantaneous point measurements for computation of diurnal-average and seasonal-average cloud radiative forcing.

5. REFERENCES

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Coefficients for equations 1, 2 and 3 available at: www.atmos.washington.edu/~fitz/param/ICSHMO7.htm.