FINAL REPORT ON VALIDATION OF MODIS SNOW AND SEA ICE PRODUCTS IN THE SOUTHERN OCEAN

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1. BACKGROUND

Validation of MODIS and Sea Ice Products in the Southern Ocean. NAG5-6338, Award amount $ 488,690; Duration, 1 October 1997 to 31 March 2003; Shusun Li and Martin Jeffries.

The purpose of this study is to validate and promote the utilization of the MODIS snow cover, sea ice cover, and sea ice temperature products in the Southern Ocean.

Since the beginning of the project, we have conducted three cruises in the Ross and Amundsen Seas. Two were pre-launch cruises in 1998 and 1999 and one was an after-launch cruise between 15 February and 31 March 2000. During the cruises, we made surface spectral bidirectional reflectance and albedo, total albedo, and surface temperature measurements on a total of 76 individual ice stations, including 24 stations during the austral winter cruise in 1998, 30 floes during the austral summer cruise in 1999, and 22 stations during the austral summer cruise in 2000.

2. MAJOR RESULTS OF INVESTIGATION OF MODIS SEA ICE PRODUCTS, AND SNOW/SEA ICE ALBEDO AND BRDF

2.1 MODIS Sea Ice Product Validation

We have been supported by the NASA EOS validation program to validate the MODIS sea ice extent product in the Ross, Amundsen and Bellingshausen Seas, Antarctica. We obtained data during three cruises: two pre-launch cruises in austral autumn 1998 and summer 1999, and one after-launch cruise in February and March 2000. During the cruises we made surface spectral bi-directional reflectance distribution function (BRDF) and albedo, total albedo, and surface temperature measurements, and other observations at a total of 76 individual ice stations. The data sets collected in those field campaigns verified the reliability of the MODIS sea ice extent product (Li et al., 2001).

It has been observed that the surface albedo of austral summer sea ice increases with latitude, while snow surface temperature decreases with latitude (Zhou et al., 2001). The higher albedo at more southern stations is observed to be associated with the lower snow surface temperature and the resulting lower liquid water content and smaller effective grain size in the upper portion of the snow.

The MODIS-derived surface spectral reflectance and field measurements have been compared (Zhou and Li, in press). During the summer cruise in February through March 2000, spectral albedo and directional reflectance of snow and sea ice were measured on sea ice of various types, including nilas, grey ice, pancake ice, multi-year pack ice, and landfast ice in the Ross, Amundsen and Bellingshausen seas. Measurements were made using a spectroradiometer that has 512 channels in the visible and near-infrared (VNIR) region in which 16 of the 36 bands of the Moderate Resolution Imaging Spectroradiometer (MODIS) are covered. Directional reflectance is also retrieved from the MODIS radiometrically calibrated data (Level 1B) concurrently acquired from the first NASA Earth Observing System (EOS) satellite, Terra. The locations of the concurrent ice stations are identified accurately on the MODIS images, and the spectral albedo and directional reflectance values at the 16 VNIR MODIS bands are extracted for those pixel locations. The MODIS-derived reflectance is then corrected for the intervening atmosphere whose parameters are retrieved from the MODIS atmospheric profiles product (MOD07_L2) for the same granule. Meanwhile, the corresponding spectral albedo and directional reflectance at the same viewing geometry as MODIS are derived from ground-based spectroradiometer measurements. As the footprint of the ground spectroradiometer is much smaller than the pixel sizes of MODIS images, the averaged spectral reflectance and albedo in the vicinity of each ice station are simulated for the corresponding MODIS pixel from ground spectral measurements by weighing over different surface types (various ice types and open water). Values of ground-based MODIS spectral simulation are compared with satellite-derived values so that the discrepancy is estimated (Figure 1).

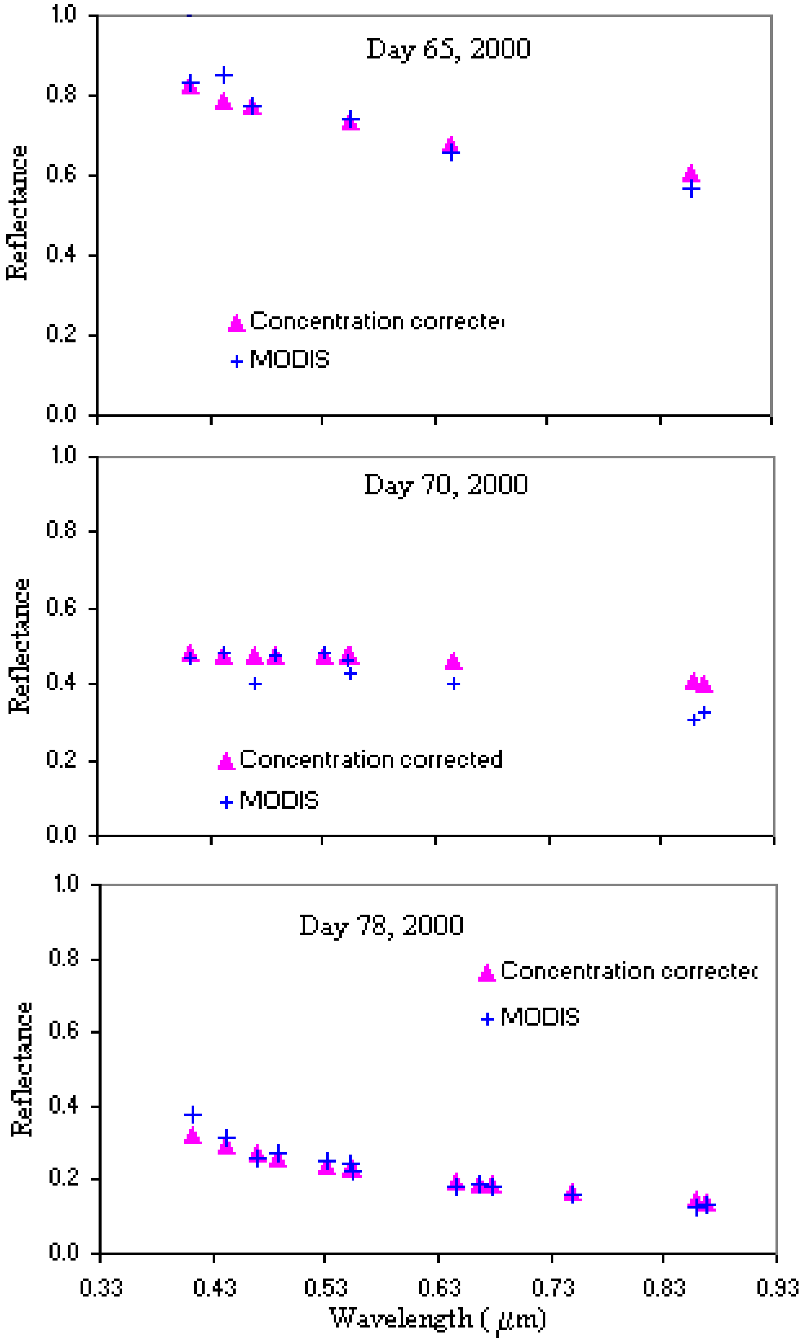


Figure 1 Comparison between MODIS-derived and *in situ* reflectances.

Comparison between MODIS-derived and *in situ* reflectances shows that, agreement is good when the ice concentration is 10/10 with the most coverage similar in reflectivity (as on day 65, with discrepancy range being 0.2-11.6%, and the average agreement within 4.8%) or when the pixel is one ice type dominated and the measurement is taken on the dominated ice floe (as on Day 78, with discrepancy being 0.8-16.9%, average difference within 6.4%). For the pixel that contains more than one ice types (day 70) that are substantially distinct in surface reflectance, worse agreement (discrepancy range is 1.2-25.1%, average discrepancy is as much as 8.2%) occurred. With the ground site very inhomogeneous and surface topography very variable, comparison for such conditions can be very difficult or even incomparable. Especially, considering that the MODIS data were acquired during its commissioning phase and the calibration of the MODIS data is not optimal, small discrepancy between the MODIS-derived and in situ measurements is understandable.

To facilitate the comparison of MODIS data sets with the field measurements, sea ice surface spectral directional reflectance and spectral BRDF were studied (Zhou and Li, 1999, 2000; Li and Zhou, 2001, 2002a, 2002b). In addition, sea ice surface albedo, and its spatial variability in the Antarctic summer pack ice were investigated (Zhou et al., 2001; Li and Zhou, 2001).

Snow covered sea ice surface spectral albedo is simulated using radiative transfer model with field measurements of snow texture and stratigraphy (Zhou, 2002). It is found that the modeled spectral albedo computed from the multi-layer model agrees better with the measured albedo when the measured composite grain-size rather than the measured single grain-size is adopted (Figure 2). Simulation results also indicate that radiation at near infrared (NIR) wavelengths is more sensitive than visible radiation to snow grain size for a vertically homogeneous snowpack, and especially to the grain sizes in the topmost layers for a vertically heterogeneous snowpack. Visible light is sensitive to snow properties within a much larger snow-depth range than NIR radiation. This result confirms the importance of the vertical distribution of snow grain size in determining the spectral pattern of surface albedo of polar snow cover (Grenfell et al., 1994; Aoki et al., 2000) although the topmost grains in the snow cover on austral summer sea ice were much coarser than those in other studies.

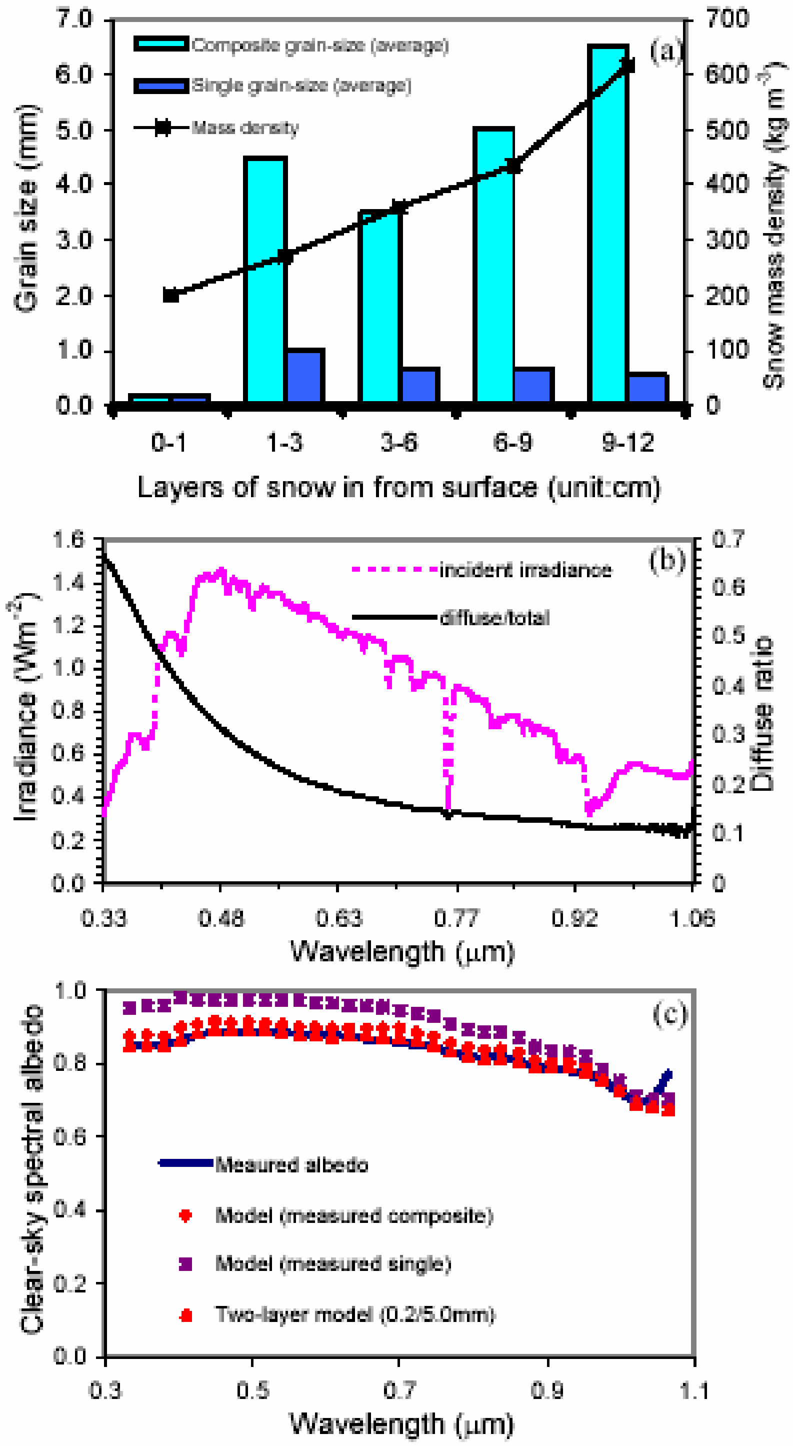


Figure 2 Comparison of modeled spectral albedo with measured spectral albedo. (a) Vertical profile of composite and single grain-size and snow density. (b) Incident spectral irradiance and

ratio of diffuse to total irradiance. Solar zenith angle θ_0 = 56°. (c) Measured spectral albedo and modeled results. A two-layer model (0.2 mm/ 5.0 mm) is also used to simulate the measurement.

2.2 A New Method for Deriving Direct Beam Spectral Albedo

We have conceived a new method for deriving snow covered sea ice surface direct beam spectral albedo using surface directional spectral reflectance measured under overcast conditions (Li and Zhou, 2001). The new method is based on the reciprocity between directional-hemispherical and hemispherical-directional spectral reflectance values (Siegal and Howell, 1981). The assumption behind the reciprocity is that the ground-level sky diffuse light is perfectly isotropic. We were aware that the method may not have a practical application because the isotropic sky diffuse light assumption may hold true only for a very narrow range of incident solar wavelengths, solar illumination angle above clouds, and cloud optical thicknesses. To address these concerns, we recently investigated whether the method can produce accurate results of snow surface direct beam albedo under typical overcast conditions (Li and Zhou, submitted).

A theoretical analysis of the errors resulting from anisotropy in sky diffuse light revealed that the error should be proportional to the covariance of the zenith-dependent and azimuthally-averaged sky diffuse radiation and surface bidirectional reflectance. Consequently, the error would be small when the sky diffuse light varies randomly. For general overcast conditions, therefore, we focused on situations in which sky diffuse light would exhibit a non-random variation.

A multi-layer zenith- and azimuth-dependent radiative transfer model (Li et al., 1987) was used to simulate both direct beam spectral albedo under clear skies (Figure 3) and surface directional spectral reflectance under various overcast conditions. Then we assessed the practicality of the reciprocity method by comparing the two sets of simulation results, and determining the impact of departure from perfect isotropic sky diffuse light on the accuracy of the results.

Simulations suggest that the sky diffuse light is almost isotropic in all the visible wavelengths under experiment for typical stratus cloud optical thicknesses (τ=10-60), and cloud droplet sizes (4-14 microns). This confirms the visual observation of the isotropy of sky diffuse light under stratus clouds. As a result, the direct beam albedo estimates in the visible wavelengths derived by the reciprocity method do not depend on cloud optical thicknesses, cloud droplet sizes and solar illumination angles above the clouds. The estimates are accurate to within ±0.01 for all cases except for extremely large solar zenith angles (>88°) (Figure 4). At NIR to shortwave infrared wavelengths, sky diffuse light is anisotropic. Nevertheless, results are also independent of cloud conditions for typical stratus cloud optical thicknesses (τ=10-60) and cloud droplet sizes (4-14 microns), and are accurate to within ±0.01 for all solar zenith angles smaller than 74° at 862 nm and for all solar zenith angles smaller than 63° at 2250 nm. Thus, the reciprocity approach can provide accurate direct beam spectral albedo estimates that complement those from the traditional method.

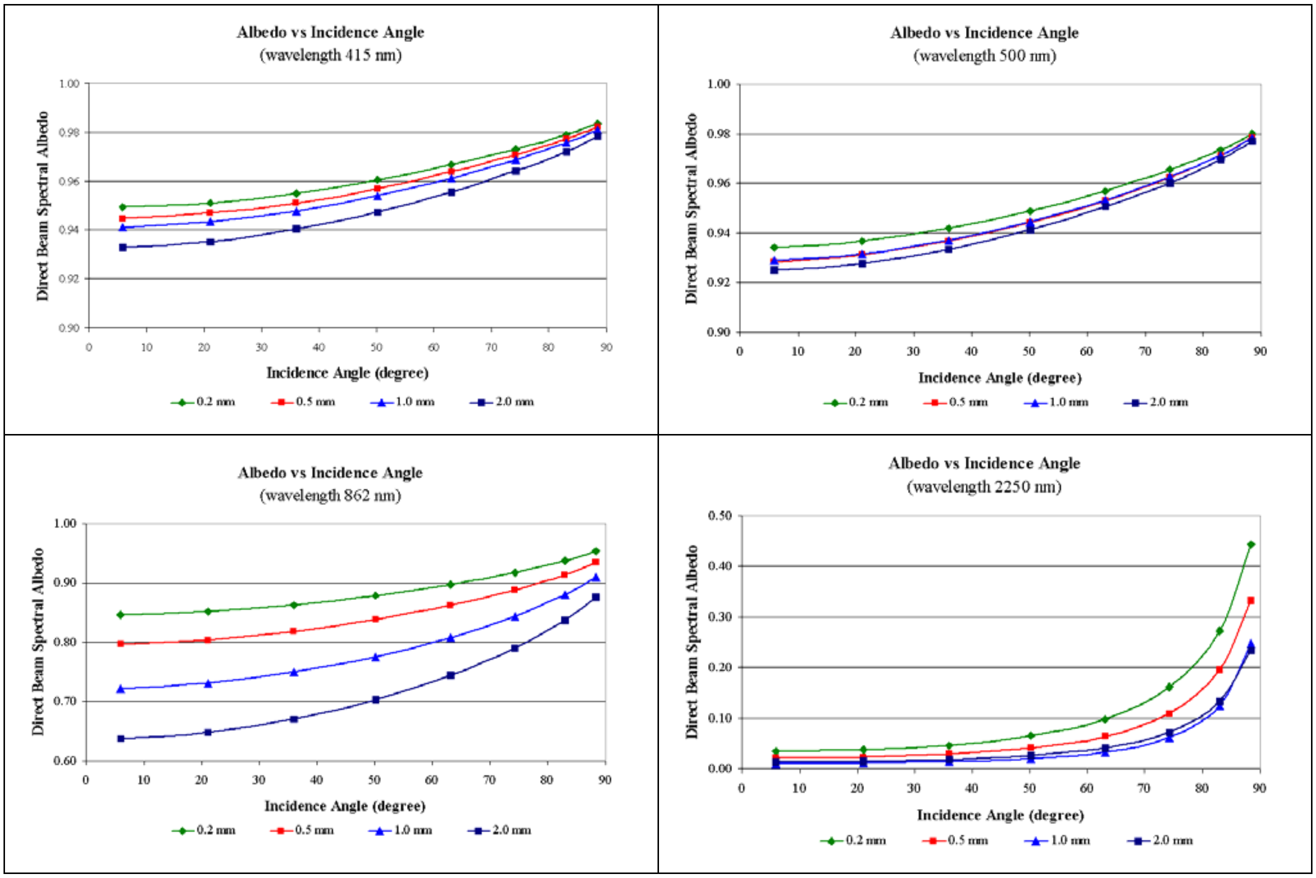


Figure 3. Direct beam spectral albedo as a function of solar incidence angle and snow grain size at wavelengths: (a) 415 nm, (b) 500 nm, (c) 862 (nm), and (d) 2250 nm.

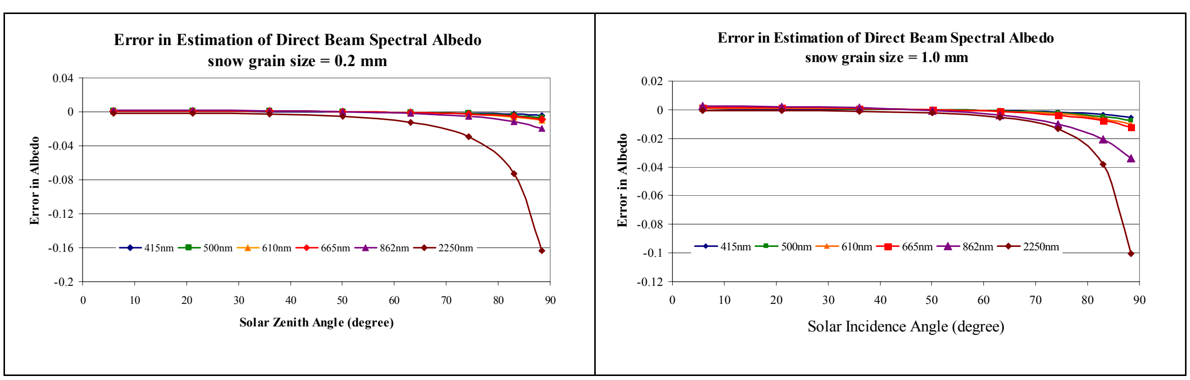


Figure 4. Error in estimates of direct beam spectral albedo as a function of solar zenith angle for snow cover with (a) snow grain size = 0.2 mm, and (b) snow grain size = 1.0 mm.

Because the relative patterns of the sky diffuse light do not vary substantially with surface types, and the theoretical derivation of the new method is general, the method is likely to be applicable at visible and NIR wavelengths for any Earth surfaces wherever the sky is not obscured by trees and buildings. A tundra surface meets such conditions well, because it is generally flat and vegetation is low-lying.

2.3 A New Method for Normalization and Optimal Parameterization of BRDF

To derive useful expressions of BRDF for individual surface types, we have developed a new method to normalize surface BRDF (Li and Zhou, 2002b). For a given surface type, the method adjusts for variations of surface direct beam albedo due to change of site, incidence angle, and even wavelength. The normalization scheme starts with a reference clear-sky BRDF data set that can be any BRDF set obtained at a representative site. The reference data set does not need any adjustment. The other data set is adjusted using the following formula:

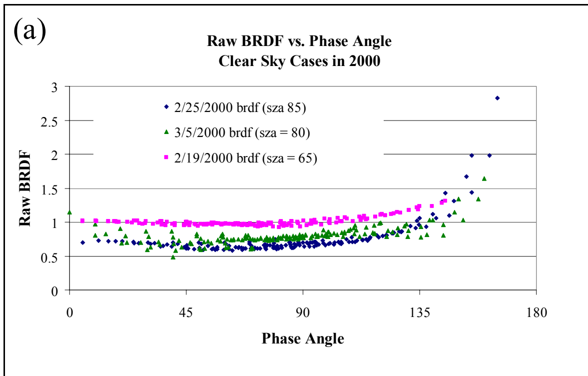
$$BRDF_{adj}(case;\lambda;\theta_o;\theta_v,\phi) = BRDF(case;\lambda;\theta_o;\theta_v,\phi)\frac{\alpha(case_{ref};\lambda_{ref};\theta_{ref})}{\alpha(case;\lambda;\theta_o)}\frac{\alpha(case_{other};\lambda;\theta_o)}{\alpha(case_{other};\lambda;\theta_{ref})},$$

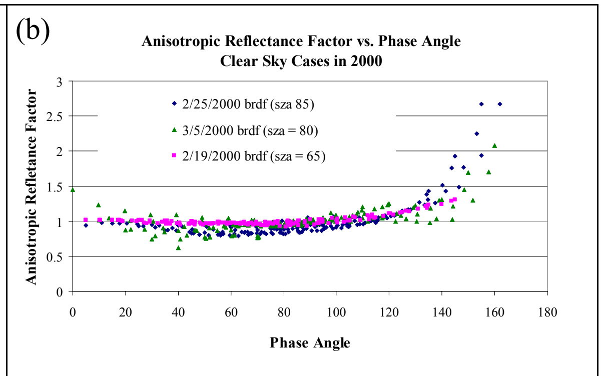
where α is albedo, λ is the wavelength, θ_o is the solar incidence angle, θ_v is the viewing zenith angle, and ϕ is the viewing azimuth angle relative to solar azimuth angle. The variable *case* indicates the site of interest, $case_{ref}$ is the reference site, and $case_{other}$ can be any site or model from which the ratio of direct beam albedo values at incidence angles θ_0 and θ_{ref} is known and representative for the site of interest. The subscript $_{adj}$ denotes adjustment, and the subscript $_{ref}$ denotes the reference site, wavelength or solar incidence angle for which the reference data set is selected. The formula includes two adjustments. The first ratio represents an adjustment due to difference in direct beam albedo values between the reference site and the site of interest. The second ratio adjusts the variation of the direct beam albedo due to the change of the incidence angle caused by the first ratio. This treatment differs from the simple normalization given by the anisotropic reflectance factor, which is

$$\xi(case;\lambda;\theta_o;\theta_v,\phi) = \frac{BRDF(case;\lambda;\theta_o;\theta_v,\phi)}{\alpha(case;\lambda;\theta_o)}.$$

Figure 5 illustrates the difference between the two treatments on the BRDF data sets we obtained during our 2000 cruise in the Amundsen Sea. The horizontal axis, i.e., the phase angle, is the angle between the incident direction and the viewing direction. The higher BRDF values with increasing phase angles indicate the strong forward scattering nature of the surface. Neither the raw BRDF nor the anisotropic reflectance factor normalization (Figs. 5a and 5b) give an optimal picture of the resemblance among the BRDF patterns measured on different deformed thick first year ice and multi-year ice floes in the Southern Ocean. The pattern produced by the new method (Fig. 5c) provides the best result in normalization.

We further attempted to derive a kernel function (Strahler et al., 1999) of snow-covered sea ice surface BRDF using both field measured BRDF and reciprocally-derived surface direct beam albedo (Li and Zhou, 2002b). We combine the resulting data sets to determine the coefficients of the BRDF kernel functions through stepwise linear regression. Because the direct beam spectral albedo set derived from the reciprocal method (Li and Zhou, submitted) covers a wide range of solar incidence angles, the derived BRDF kernel functional expression is optimized in the sense that the ordinary limitation of narrow solar zenith angle range no longer exists. A complete set of BRDF values can then be calculated in terms of full ranges of solar and viewing zenith angles, and relative azimuth angles. This method will be used for optimization of BRDF of the surface types of interest on the North Slope of Alaska. The resulting BRDF expression will contribute to improving the derivation of surface albedo from remote sensing measurements.





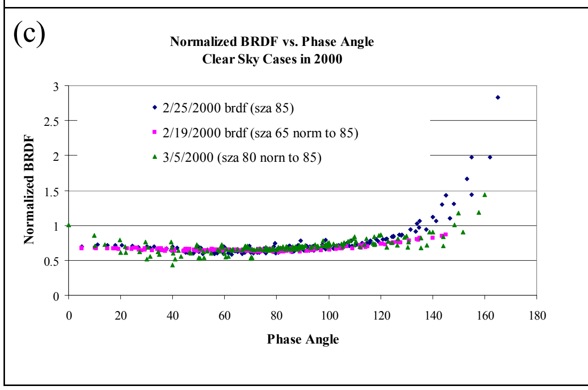


Figure 5. (a) Raw BRDF, (b) anisotropic reflectance factor, and (c) normalized BRDF patterns on 19 and 25 February, and 5 March 2000. The patterns in Fig. 5c are based on the use of our new method.

We will use the knowledge gained and the new method developed during this investigation for future snow and ice investigations.

2.4 Xiaobing Zhou received his Ph.D. degree under the support this NASA funding

Mr. Xiaobing Zhou was recruited for this project. He participated in three cruises, processed and analyzed the field data sets, simulated sea ice surface albedo using radiative transfer model based on field measured snow texture and stratigraphy, and made comparison among field measurements, model simulation and MODIS measurements. He completed his Ph.D. thesis titled "*Optical Remote Sensing of Snow on Sea Ice: Ground Measurements, Satellite Data Analysis, and Radiative Transfer Modeling"* and was conferred a Ph.D. in Geophysics at the University of Alaska Fairbanks in August 2002. He is a research assistant professor at New Mexico Tech.

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