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How does snow impact the albedo of vegetated land surfaces as analyzed with MODIS data?

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[1] Albedo derived from MODIS observations is found to be very stable during November 2000–January 2001. We analyze shortwave albedo under snow and snow-free conditions by IGBP land cover types. Snow changes the spectral property of the surface reflectivity and causes high heterogeneity in the surface albedo between and within land types. The mean black sky (or direct beam) albedo at local solar noon for snow-covered forests is less than 0.30 in the shortwave (0.3–5.0 μm), but it reaches 0.57 for snow-covered grassland and barren. Although we are unable to further separate within-class albedos with fractional tree cover, we find that the normalized difference snow index (NDSI) is highly correlated with surface albedo and hence can be taken as a measure of snow, soil and canopy fraction. *INDEX TERMS:* 3322 Meteorology and Atmospheric Dynamics: Land/atmosphere interaction; 3359 Meteorology and Atmospheric Dynamics: Radiative processes; 3360 Meteorology and Atmospheric Dynamics: Remote sensing; 3394 Meteorology and Atmospheric Dynamics: Instruments and techniques

1. Introduction

[2] Terrestrial surfaces with snow cover can be highly reflective of solar radiation but it has been difficult to quantify the albedos of the land component of climate models under such conditions because of potential masking effects of tall vegetation. A lowering of surface albedo from that of pure snow by the shading of the forest canopy was observed from aircraft by *Robinson and Kukla* [1984] over a mixed forest in southeastern New York State and more recently by *Betts and Ball* [1997] over boreal forests. The latter found albedos seldom exceeded 0.3. Climate modelers have also found large increases in the absorption of solar radiation by snow covered surfaces when shading of the snow by canopies was assumed, and consequent increases of surface temperature as compared to the high values of winter albedo of bare ground (e.g., *Bonan et al.* [1992]). *Viterbo and Betts* [1999] showed that reducing the albedo of snow surfaces from 0.8 to 0.2 for boreal forests in the European Centre for Medium-Range Weather Forecasts (ECMWF) model largely eliminated that model's systematic cold bias over boreal forests in the spring.

[3] Satellite remote sensing offers a broad view of surface albedo due to its large spatial scale and coverage. This paper summarizes the winter albedo for snow-covered and snow-free land surfaces north of 40°N latitude, using the provisional product of the directional hemispherical reflectance (or black sky albedo at local solar noon) from MODerate Resolution Imaging Spectroradiometer (MODIS) acquired during November 2000–January 2001.

2. Data

[4] The MODIS BRDF/Albedo algorithm uses a three-parameter semiempirical RossThickLiSparse-Reciprocal BRDF model to characterize the anisotropic property of land surface reflectance [*Wanner et al.*, 1997; *Schaaf et al.*, 2001]. BRDF model parameters are retrieved from cloud-free atmospherically corrected surface reflectances during each 16-day period. Seven spectral and three broadband (0.3–0.7 μm, 0.7–5.0 μm, and 0.3–5.0 μm) albedos are then derived from the BRDFs through angular integration and spectral to broadband conversion. When there are less than seven clear looks, or observations do not fit the BRDF model well during a 16-day period, albedos are retrieved with a backup method using available observations to adjust *a priori* knowledge of surface BRDFs [*Strugnell and Lucht*, 2001].

[5] The MODIS Cloud Mask product uses a threshold of 0.4 for normalized difference snow index (NDSI) and ancillary snow maps to identify snow/ice backgrounds [*Ackerman et al.*, 1998; *Hall et al.*, 1995]. The reflectance of snow is high in the visible (MODIS band 4) and low in the mid-infrared (MODIS band 6) [*Wiscombe and Warren*, 1980]. This differentiates snow from other land material and cloud. The snow/ice flag is turned on and stored in Quality Assurance (QA) fields in the MODIS albedo product if the majority of observations during a 16-day period are indicated as snow/ice and in such a case only those observations are used for the BRDF/Albedo snow inversion.

[6] MODIS surface reflectance and BRDF/albedo products were upgraded to a provisional status starting with data from October 31, 2000. Note that the aerosol correction was applied only with a constant aerosol optical depth of 0.05 over snow in the current at-launch atmospheric correction algorithm. The MODIS provisional land cover product, with a one-kilometer resolution, is used to divide the land surfaces according to the International Geosphere-Biosphere Project (IGBP) 17-class land cover types [*Friedl et al.*, 2001]. We also use a fractional tree cover data set derived from 1992-1993 NOAA AVHRR data in attempting to estimate the extent of forest shadowing of snow [*DeFries et al.*, 1999].

3. Results and Discussions

[7] Land surface models such as the Biosphere-Atmosphere Transfer Scheme (BATS) represent the albedo of a grid box as an average of soil albedo, vegetation albedo and snow albedo weighted by the respective area fractions [*Dickinson et al.*, 1993]. The albedo

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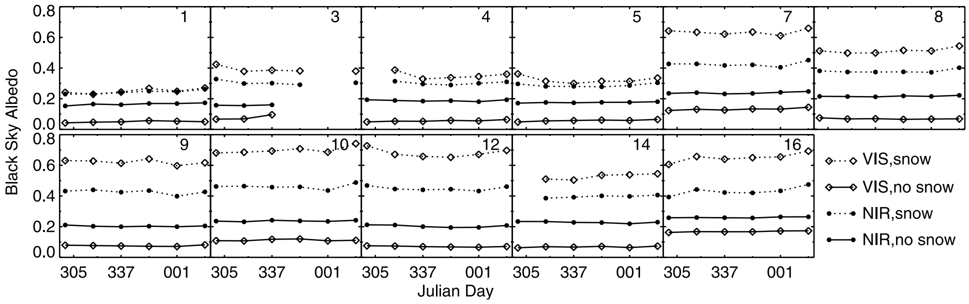

Figure 1. Temporal sequence of mean black sky albedos in visible and infrared for various IGBP types between 40°N and 50°N. IGBP code is shown in the upper right corner of each panel. See Figure 3 caption for type names.

of snow-covered lakes and permanent snow/ice is representative of the albedo of pure snow. For snow-covered lakes, the mean values of visible (0.3–0.7 μm), infrared (0.7–5.0 μm), and total shortwave (0.3–5.0 μm) albedo are 0.837, 0.516, and 0.667, respectively, with standard deviations all less than 0.06. Similar values are found over Greenland between 60°N and 70°N with means of 0.879, 0.493 and 0.665, respectively.

[8] Figure 1 shows temporal sequences of mean snow-covered and snow-free albedos in visible and infrared for the IGBP classes with more than 10000 pixels between 40°N and 50°N. Albedo changes little within the three winter months. The MODIS black sky albedo is generated at local solar noon, but solar zenith angle varies by only 5° during this period. Hence, albedo should not vary much with solar zenith. Albedos are higher and have different spectral properties when the land is covered by snow. Vegetation has particularly low albedos in the visible because of the absorption by leaf pigments, while snow has its highest albedos in the visible. Figure 1 suggests that the spectra and magnitude of albedos are dominated by those of snow for sparsely vegetated and barren land, whereas where there are extensive branches and leaves overlying snow albedos are either somewhat or much closer to those of the corresponding snow free surfaces, depending on how much of the canopy itself is covered by snow. Quantification of the albedo of snow covered surfaces according to land cover is addressed here.

[9] In addition, mean winter values of albedo are derived (averaging over October 31, 2000–February 1, 2001) for each pixel under snow-covered and snow-free conditions, respectively. The mean composite image (Figure 2) presents a spatial distribution of albedo that generally follows the patterns of land cover type (Figure 3), especially the distributions of tall and short vegetation. We summarize the means and standard deviations of snow and snow-free shortwave albedos by IGBP class individually for two latitude bands (Southern tiles: 40°–50°N and Northern tiles: 50°–60°N). Statistics are presented in Table 1 only for southern tiles. Under snow free conditions, land shortwave albedos rarely exceed 0.2 except for the barren class and the standard deviations are relatively small, ranging from 0.02 to 0.07.

[10] Albedos with snow cover are increased to varying degrees. That of forests generally increases less with snow conditions than that of other land cover types. Mean solar zenith angles at local solar noon north of 40° in winter are larger than 65°, and boreal forests are dominated by high vegetation canopy with more than 60 percent coverage. These two factors contribute to the large fraction of shadows [*Ni and Woodcock*, 2000] and hence large reduction of the albedo from that of snow alone. Evergreen needleleaf forests have the smallest albedo with a mean value of 0.21 for total solar broadband. Field measured albedos for jack pine and spruce/poplar with snow are 0.150 (±0.051) and 0.108 (±0.092) in Canada boreal forest, respectively [*Betts and Ball*, 1997]. Deciduous forests have higher snow albedo than evergreen needleleaf forests, with the mean value around 0.29. The highest value of albedo measured by an Eppley pyranometer (0.3–3.0 μm) is 0.25 over a leafless, deciduous aspen stand with snow north of Prince Albert, Saskatchewan in Canada [*Hardy et al.*, 1998]. The albedo of mixed forests are between those of evergreen needleleaf forest and deciduous forests as expected.

[11] In general, mean albedos of forests with underlying snow are lower than 0.30, in agreement with in situ measurements in winter boreal forests [*Betts and Ball*, 1997]. However, the winter forest albedo values from MODIS are larger than those cited from in situ observations. The field measurements were made at low levels over the canopy, but satellites may see a larger fraction of sunlit gaps between forest stands and hence higher albedo. Moreover, snow is hard to detect when presence of vegetation shading is very strong [*Hall et al.*, 1995]. This may bias the forest mean albedo in the MODIS data towards relatively sparse forests. The under-corrected aerosol effect is another possible reason for the higher albedos of snow-covered forests derived from MODIS observations.

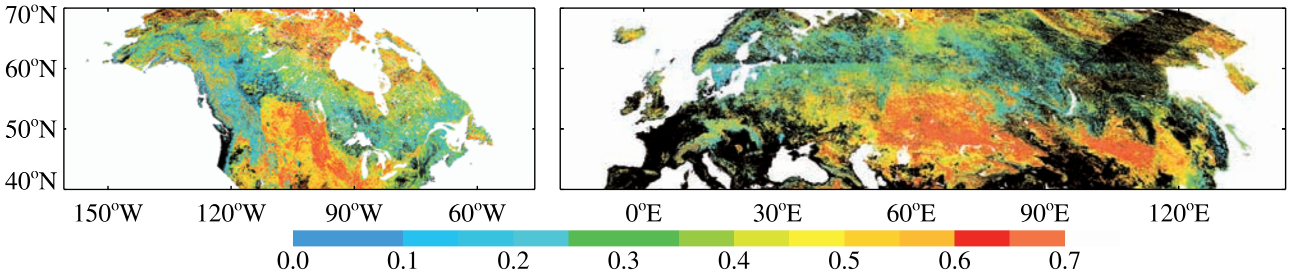

Figure 2. Mean shortwave black sky albedo under snow conditions in North America (left panel) and Eurasia (right panel) from 40°N to 60°N during November 2000–January 2001 and from 60°N to 70°N during November 2000. The image is in Interrupted Goodes projection. Pixels without retrievals due to cloud contamination are in black.

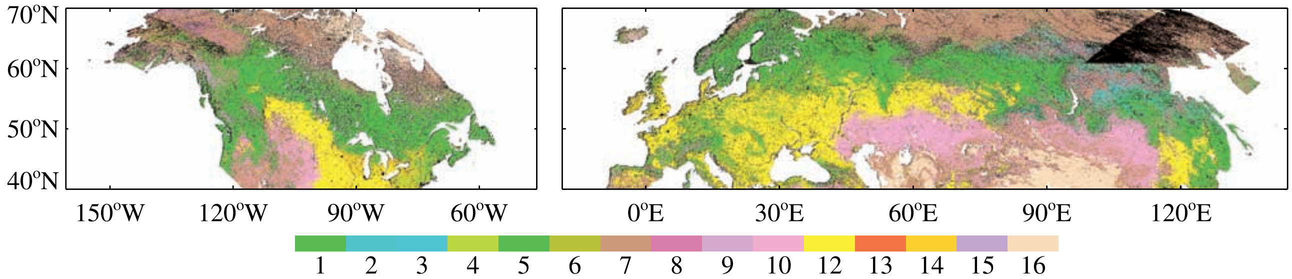

Figure 3. MODIS provisional IGBP land cover map over the same region as Figure 2. IGBP 1. Evergreen needleleaf forests; 3. Deciduous needleleaf forests; 4. Deciduous broadleaf forests; 5. Mixed forests; 6. Closed shrublands; 7. Open shrublands; 8. Woody savannas; 9. Savannas; 10. Grasslands; 12. Croplands; 13. Urban and built-up lands; 14. Cropland/Natural vegetation mosaics; 16. Barren. Non-classified pixels are in black.

[12] Of the vegetated IGBP classes, grasslands show the highest albedo, with a mean value of 0.57, similar to that of barren surfaces but significantly smaller than the 0.67 inferred for pure snow from lakes and Greenland. The snow mostly buries the vegetation for this cover but some trees or other shadowing objects may remain. Croplands also have very high albedo in winter consistent with being denuded by harvesting. The MODIS-derived albedo of snow-covered grasslands is substantially lower than the mean value of 0.75 (±0.10) measured at BOREAS mesonet stations [*Betts and Ball*, 1997], however. The latter may have excluded any shadowing objects as a similar value is used in BATS for pure snow as derived from the measurements of *Wiscombe and Warren* [1980]. MODIS-derived shortwave albedo for Greenland is also lower than the typical albedo of 0.83 measured with Eppley Precision Spectral Pyranometer [*Stroeve et al.*, 2000].

[13] It is evident that either the MODIS albedo estimates for bright surfaces such as snow have a low bias or the satellite instrument is seeing significant shadowing by snowdrifts and/or dirty or large crystal snow surfaces. While the Eppley pyranometer does not cover the 3.0–5.0 μm spectrum where snow has a much lower albedo, this component of the spectrum contributes little to total albedo. A low bias may be the effect of aerosols in reducing the albedo of highly reflective surfaces. Such a reduction may be as high as 0.10 at 0.50 μm for an aerosol thickness of 0.05 [*Li and Garand*, 1994]. On the other hand, field observations measure the albedo under both the direct and diffuse illumination while MODIS derives its black sky albedo under direct beam at local solar noon. Moreover, the current MODIS narrowband to broadband conversion coefficients [*Liang et al.*, 1999] are not specially developed for pure snow, which may lead up to a 10 percent lower bias in the shortwave albedo for pure snow (S. Liang, personal communication, 2001). This, however, has little effect on land surfaces where the non-snow spectral signals are dominant such as forest.

[14] Open shrublands, savannas and cropland/vegetation mosaics, all with less than 60 percent of canopy coverage, have similar shortwave albedos around 0.46, indicating significant shadowing. The mean shortwave albedo of open shrublands decreases from 0.45 in the southern tiles to 0.40 in the northern tiles, and that of cropland/vegetation mosaics from 0.46 to 0.39. It is possibly a consequence of a greater shadowing from lower sun angles in northern tiles by 10°. Woody savannas contain a mosaic of trees and short vegetation, and hence have a larger (or smaller) fraction of shadows than that of short vegetation (or forests). Therefore the albedo of this class (under snow or snow-free condition) is in between those of deciduous forests and short vegetation (e.g., savannas), as indicated by Table 1.

[15] Surface reflectivity is more heterogeneous in the presence of snow, hence the value for any given pixel is more uncertain as shown by the higher standard deviation of the albedo within each land cover type (Table 1). Estimates of fractional tree cover [*DeFries et al.*, 1999] are first used to attempt an analysis of the within-class variance of the albedo but the result is not significant. However, we find that NDSI (estimated from the normalized differences between black sky albedos of MODIS channel 4 (545–565 nm) and 6 (1628–1652 nm) can represent the fractions of snow, soil and vegetation to some degree as its correlation coefficient with albedo is as high as 0.6. Table 2 shows the means and standard deviations of shortwave albedo for two thresholds of NDSIs by IGBP. Albedos of snow covered surfaces of a given land type are lower by an amount comparable to the standard deviation for a lower NDSI. However, this correlation is statistically significant only for forests in the data examined.

Table 1. Snow and Snow-Free Black Sky Albedos in the Shortwave (0.3–5.0 μm) Broadband Over 40°–50°N

	Snow Free		Snow	
IGBP	Area	Mean (std)	Area	Mean (std)
1	35.5	0.105 (0.035)	34.2	0.213 (0.095)
3	0.5	0.127 (0.046)	0.6	0.296 (0.122)
4	28.1	0.122 (0.021)	16.6	0.294 (0.090)
5	115.5	0.112 (0.028)	85.6	0.269 (0.096)
7	7.1	0.153 (0.046)	13.9	0.449 (0.148)
8	6.3	0.137 (0.034)	4.2	0.389 (0.140)
9	0.5	0.142 (0.037)	0.4	0.472 (0.129)
10	203.0	0.169 (0.045)	251.0	0.575 (0.097)
12	85.3	0.141 (0.027)	63.1	0.510 (0.105)
14	9.9	0.150 (0.020)	8.6	0.463 (0.098)
16	133.9	0.205 (0.037)	50.5	0.544 (0.110)

Area is in unit 10^4 km^2. Statistics are not calculated for tiles with snow area less than 1000 km^2. See the caption of Figure 3 for IGBP codes.

Table 2. SW Snow Albedos Differentiated by NDSI

	Low NDSI		High NDSI	
IGBP	Area	Mean (std)	Area	Mean (std)
1	10.8	0.158 (0.052)	17.4	0.234 (0.082)
3	0.1	0.189 (0.050)	0.4	0.318 (0.098)
4	4.1	0.222 (0.053)	11.1	0.314 (0.075)
5	25.3	0.205 (0.053)	51.1	0.297 (0.083)
7	4.4	0.355 (0.122)	8.9	0.498 (0.131)
8	2.5	0.371 (0.122)	1.3	0.469 (0.124)
9	0.2	0.406 (0.102)	0.2	0.527 (0.115)
10	59.9	0.506 (0.102)	186.1	0.597 (0.082)
12	24.5	0.448 (0.090)	37.1	0.553 (0.084)
14	5.6	0.426 (0.078)	2.9	0.544 (0.075)
16	16.4	0.498 (0.112)	33.0	0.571 (0.093)

Low NDSI: (0.1–0.3) for forests and (0.4–0.6) for others; High NDSI: (0.4–0.6) for forests and (0.6–0.8) for others.

4. Conclusions

[16] Our analysis of MODIS albedo data north of 40°N shows that snow changes the average spectral property of surface reflectance and causes high heterogeneity in surface albedo. The magnitude of albedo increase under snow conditions is dependent on vegetation type. Forests have the lowest albedo as expected from their high canopy density and the shading effects, while albedos of nonforested surfaces become much larger with snow but remain less than that of Greenland, presumed to have albedos of pure snow. Comparison with field measurements implies that MODIS gives higher albedos for forests but lower albedos for land types that have little canopy shading. This study suggests the need for the coincident field measurements in the presence of snow to better validate the land albedo derived from the MODIS observations. A consistent one year of reprocessed MODIS data will soon be available and the MODIS albedo algorithm will continue to be refined and improved.

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