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REMOTELY SENSED ALBEDO OF SNOW-COVERED LANDS

David A. Robinson

Lamont-Doherty Geological Observatory
of Columbia University
Palisades, NY 10964

1. INTRODUCTION

Snow cover is an important variable of the climate system. The accurate forecasting of local daily temperatures, regional climatic anomalies and the location and strength of cyclonic systems relies, in part, on knowledge of the distribution and state of regional snow cover (Dewey, 1977; Kukla, 1979; Namias, 1981; Walsh et al., 1982; Foster et al., 1983; Robinson, 1984a; Walsh and Ross, 1986). Snow-covered land exhibits major differences from snow-free ground due to snow's low heat conductivity, high thermal emissivity, low vapor pressure and high shortwave albedo.

The high albedo of snow permits the recognition of snow-covered land in shortwave satellite imagery. This task is often difficult, however, as the albedo of snow-covered land varies considerably as a function of the type and density of vegetative cover, the physical properties and depth of snow and the continuity of snow cover. Automated analyses of multi-spectral satellite imagery have shown to be promising (Kunzi et al., 1982; Bunting and D'Entremont, 1982; Tsonis, 1984). Nevertheless, an interactive analysis of satellite data on an image processor by an observer familiar with the studied area is still the optimal method of retrieving information on snow-covered regions.

In the following, examples of albedo variations of both fresh and aging snow cover are examined using a combination of remotely-sensed aircraft and satellite data. For the purpose of this discussion, only clear-sky albedo values are discussed.

2. DATA

2.1. Aircraft measurements

Surface albedo (0.28-2.80μm) was measured over typical middle latitude surface types under a variety of snow-covered conditions. Data were gathered over southeastern New York and northern New Jersey from aircraft equipped with wingtip-mounted hemispheric pyranometers. At the flight altitude of approximately 200m, 90% of the reflected signal came from an area of approximately $0.50km^2$. The confidence limit of flight albedos is ±4% of the calculated value (Robinson and Kukla, 1984).

2.2. Satellites

Surface albedo was estimated over full and partly snow-covered lands from Defense Meteorological Satellite Program (DMSP) and NOAA Advanced Very High Resolution Radiometer (AVHRR) imagery, having resolutions of 2.7km and 1.1km, respectively. Albedo was determined by analysing clear-sky scenes on a digital image processor. The brightness of the scene was converted to surface albedo by linear interpolation between bright and dark snow-covered or snow-free targets with known albedos. Shine and Henderson-Sellers (1983), using a radiative transfer scheme, have shown that this approach works well with DMSP imagery because of the wide spectral range (0.4-1.1μm) of the DMSP sensor.

Albedos so calculated from DMSP imagery may be up to 0.10 too low or 0.05 too high (Robinson and Kukla, 1985). The range is larger for the narrow band (0.6-0.7μm) AVHRR imagery. These error ranges are relatively small compared to the dramatic differences in surface albedo due to contrasting types and densities of vegetation and varying snow conditions.

3. FRESH SNOW COVER

The albedo of surfaces which are covered with fresh snow varies due to the type and density of vegetative cover and the depth of snow. The latter is exemplified in table 1, which presents aerial albedo data gathered over fresh snow-cover on two days where only the snow depth differed. On February 10 only 10-15cm of snow covered the fields and forests, while on the 14th of February 40-50cm of snow lay on the ground. Ground measurements of the albedo of pure snow on both dates were between 0.78 and 0.83. Albedo on the 10th was from 0.03-0.12 lower than on the 14th. Representative differences were 0.03-0.06 over forests, 0.05 over grassy meadow, 0.06-0.08 over developed areas, and 0.12 over shrubby grassland and cultivated fields. These differences were due to the presence of grass, bushes, crop and forest litter, rocks, rooftops, etc., which were buried on the 14th, but protruded through the pack on the 10th. In general, differences caused by varying depth are significant when less than 15 to 20cm of snow covers the ground.

The impact of vegetation on the surface albedo varies markedly over land covered by fresh snow. Figure 1 shows the potential

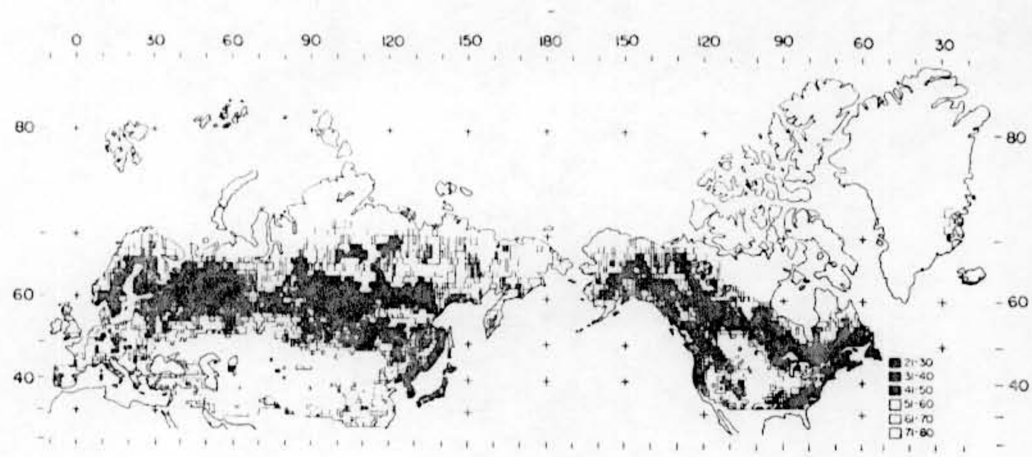

Fig. 1. Maximum surface albedo of Northern Hemisphere land with the potential of developing seasonal snow cover. Cells, measuring $1^{\circ} \times 1^{\circ}$, are marked in 0.10 increments. (from Robinson and Kukla, 1985)

Table 1. Surface albedo with differing depths of snow cover over sites representing a variety of middle latitude surfaces. On Feb. 10, 1983 the snow cover was 3 days old and 10-15cm deep. Over the same sites on Feb. 14, 1983 the top 30-40cm of the cover was 2 days old and the entire pack was 40-50cm deep. The albedo of the snowpack on both dates was between 0.78 and 0.83. For a further description of sites see Robinson and Kukla (1984).

Surface	Albedo		
	Feb. 10	Feb. 14	14th-10th
mixed forest	0.16	0.19	0.03
deciduous forest	0.25	0.31	0.06
shrubby grassland	0.48	0.60	0.12
grassy meadow	0.67	0.72	0.05
cultivated fields	0.68	0.80	0.12
suburban residential	0.40	0.48	0.08
industrial	0.51	0.57	0.06

maximum surface albedo of seasonally snow-covered Northern Hemisphere lands. Data were gathered in selected clear-sky scenes of DMSP imagery where visual inspection showed the presence of deep and stable snow cover over several consecutive days. In areas where deep snow was not found in the several years of imagery analysed, albedo was inferred. These areas were mostly located in portions of arid and semiarid southern Asia, where albedo inference is simplified by the general absence of tall or dense vegetation (Robinson and Kukla, 1985).

There is a broad zone of relatively dense forests masking the underlying snowpack in Eurasia and North America. In Eurasia, the areally averaged albedo is 0.36 over the boreal forest zone between 60° and 65°N. It rises to 0.76 over the short grassy tundra further north.

4. AGING SNOW COVER

When assessing the albedo of an aging or dissipating snow cover other factors, in addition to vegetation and depth, come into play. These include the physical properties of the snow and the areal continuity of the cover.

As the snowpack ages, the grain size increases, the surface gets dirty and eventually the pack becomes wet. As a result, the albedo continually decreases. At depths less than approximately 10cm, the underlying surface begins to influence the reflected signal. Ground measurements of an originally 50cm deep snowpack over a short grassy field showed albedo falling by 0.29, from 0.83 to 0.54, over a 13 day period (Fig. 2). While the snow was slushy by the 13th day, no grass blades had yet protruded through the pack.

The physical condition of the snowpack impacts on the albedo of all snow-covered surfaces. Aerially-measured albedos from 25 sites, including field, forest and developed areas, on a day with 10-15cm deep 3 day old snow (Feb. 10) were approximately 20% greater than at the same sites with identical snow depth but with the snow 9 days old (Feb. 22) (Fig. 3). The albedo of the uninterrupted snowpack was approximately 0.80 on the 10th and 0.60 on the 22nd.

Over lightly-vegetated regions with snow present, the largest decreases in surface albedo occur not from physical changes in the snowpack but from the exposure of bare ground. The latter may result from melt or deflation. In figure 4, brightness histograms measured from AVHRR images show the changing proportion of snow-covered and snow-free surfaces as snow dissipated over approximately $100,000km^2$ of farmland in the central U.S..

Histogram 1 shows the area in March 1976, when all of the approximately 90 climate stations in the area measured over 15cm of fresh

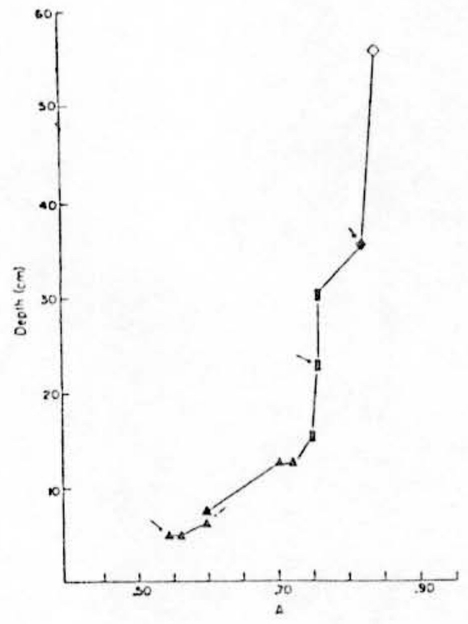

Fig. 2. Midday albedo of a complete snowpack over a short grassy field at the Lamont Observatory (41°N) from Feb. 13-25, 1983. Albedo is shown with a diamond for 1-3 day old snow (open diamond: dry, Feb. 13 and 14), squares 4-6 days old, triangles 7 days or more old. Solid symbols indicate a wet snowpack. Datum from Feb. 20 is missing. Arrows point to cases where global atmospheric transmissivity was below 40%. (after Robinson, 1984b)

Fig. 3. Snow depth-age-albedo relationships. The albedo of a site on Feb. 10, 1983 is plotted against the albedo of the identical site on Feb. 22, 1983. Both days had clear skies and the same snow depths at forest and field test sites. Snow on the 10th was 3 days old and dry with an albedo of 0.78. Snow on the 22nd was 10 days old and wet with an albedo of 0.60. The regression equation has a correlation of 0.96. (after Robinson and Kukla, 1984).

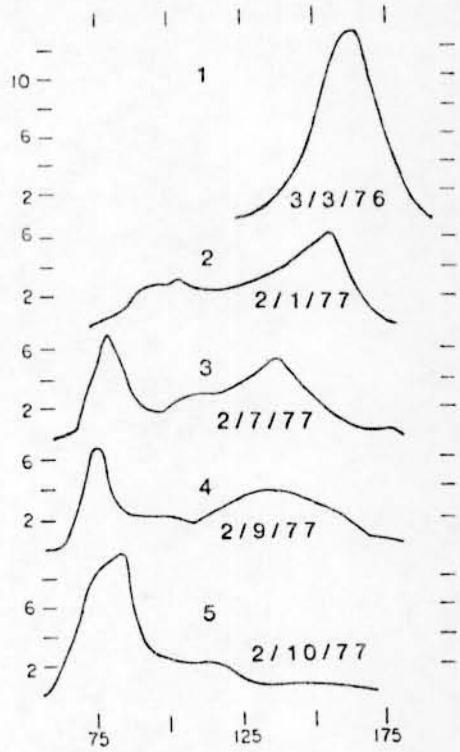

Fig. 4. Brightness histograms with different snow-cover conditions over central U.S. farmland. Vertical axis shows the number of processor pixels (x 10^{3}) with a particular brightness (horizontal axis). (after Robinson and Kukla, 1982)

snow cover on the ground. A single high brightness peak corresponded to an albedo of about 0.70. The February 1, 1977 histogram (2) quantifies the brightness distribution over the region when a snow cover was 7 days old. Some bare ground had begun to appear, giving the histogram a bimodal character. Regional albedo was approximately 0.40. Compared to histogram 1, the bright peak is shifted towards the dark end, probably due to a combination of decreasing albedo of aging snow and subresolution patches of bare ground. Some 80% of the stations in the region reported snow cover on the 1st. At these stations the average depth was 10cm.

In subsequent days (histograms 3-5), the amount of snow-free ground began to exceed that of snow-covered ground and regional albedo decreased from about 0.30 to 0.20. By the 10th, the single dark peak on the histogram (5) indicates that the surface was mostly snow free, with only subresolution snow patches probably present. These broadened the peak and skewed it towards brighter values. On this date, 50% of the stations reported snow cover, with the depth averaging 4cm.

5. CONCLUSIONS

Regions where snow is present exhibit a wide range of surface albedo due to variations in the type and density of vegetation and the depth, physical properties and continuity of the snowpack. At present, the most accurate way to assess the winter surface albedo on regional to continental scales is through the analysis of shortwave satellite imagery in an interactive manner on an image processor by an observer familiar with the studied area.

6. ACKNOWLEDGMENTS

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