Determination of Broadband Albedos of Partially Snow-Covered Sites for Validation of MODIS Snow Albedo Retrievals

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ABSTRACT

Over the period from February 24th-28th, 2003, the albedo of two partially snow-covered sites in northwestern Iowa was characterized to validate snow albedos retrieved from data collected by NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) instrument. Below average snowfall provided the opportunity to evaluate the accuracy of snow albedos retrievals from the current MODIS snow-albedo algorithm for pixels containing a mixture of snow and other surface covers. Over a frozen lake and agricultural fields, heterogeneity in albedo was observed within a single 500 m MODIS pixel. Over the frozen lake, the primary source of spatial variability was associated with snow patches alternating with lake ice over distances of a few meters. Small-scale variability in albedo was also observed on the agricultural fields, but larger-scale spatial variability due to differing land covers and redistribution of snow by wind also occurred. At both localities, snow albedo was measured at random sampling localities within a series of 10 m grid cells. On the agricultural fields, albedo measurements were also made on a 250 m grid. Geographic Information System (GIS) techniques were employed to integrate these *in situ* albedo measurements into estimates of broadband albedo representative of MODIS pixels for comparison with albedos retrieved from MODIS. In general, MODIS snow albedos were within 10% of those measured *in situ.* Decreases in the MODIS retrieved albedos over the study period were also consistent with those observed on the ground.

Keywords: remote sensing, albedo

INTRODUCTION

Currently a suite of snow cover products (described in detail in Hall *et al.* 2002) are being produced from data collected by Moderate Resolution Imaging Spectroradiometer (MODIS) instruments currently operating aboard NASA's Terra and Aqua satellites. These products are produced using an automated algorithm and are providing global, daily snow cover maps at 500 m spatial resolution that are publicly distributed by the National Snow and Ice Data Center (NSIDC). Beginning in September 2003, a global daily snow albedo product will be produced and distributed as a 'beta test product.' The algorithm which is described in detail in Klein et al. (2000) and Klein and Stroeve (2002) is one of several approaches that have been used to determine the abledo of snow from satellite (e.g., Robinson and Kukla, 1985; Knap and Oerlemans, 1996; Stroeve *et al.* 1997).

The existing MODIS snow cover products have been validated by a number of published studies (e.g., Bitner *et al.* 2002; Klein and Barnett, 2003; Maurer *et al.* 2003). However, development of the snow albedo product is still underway and validation has been limited. Measurement of snow

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albedo has a long history and several studies have been compared snow albedos measured by satellites against ground observations (e.g., Stroeve *et al*. 2001; Zhou *et al*. 2001).

One fundamental issue in any comparison between *in situ* field measurements and a satellite observation is the how well a single or small number of ground measurements represent the area viewed by the satellite. The scaling issue increases as the resolution of the satellite sensor decreases and as the heterogeneity of the target increases. In this study, scaling issues between ground observations of albedo and that measured at the satellite are addressed by employing a randomized spatial sampling scheme to obtain unbiased estimates of surface albedo at two spatial scales for comparison with satellite-derived albedos.

Successful validation of a snow albedo algorithm requires clear skies, sub-freezing temperatures and, of course, snow cover. During February 24th to 28th, 2003, the intent was to validate MODIS snow albedo retrievals using large uniform snow covered fields located on the low relief topography of the Des Moines Lobe in northern Iowa. However, Iowa snowfall during the winter of 2002-2003 was considerably below historic climatic means. Therefore, the opportunity presented itself to assess the accuracy of MODIS snow albedo retrievals for marginal snow conditions where the ground was covered in a mixture of snow and other land covers. Such conditions are not atypical of snow conditions in many regions of the world.

The study also examined the feasibility of using inexpensive LI-COR pyranometers for validating MODIS snow albedo measurements. Henneman and Stefan (1998) compared daily albedos measured on Ryan Lake in Minneapolis, Minnesota using LI-COR and Kipp & Zonen thermocouple pyranometers for the period from December 17, 1996 to March 21, 1997. They found that LI-COR pyranometers could be successfully used to measure short-wave albedo on snow and ice surfaces on a daily basis. This study performed a small comparison of the albedos retrieved from three types of pyranometers over the short time periods typical of field validation of satellite albedo retrievals.

STUDY AREA

The three sites used in this study are located in Dickenson County, Iowa (Figure 1). The sites are underlain by glacial deposits of the Des Moines Lobe which was created by a surging ice front along the southern margin of the Laurentide ice sheet some 14,000 to 12,000 BP (Prior, 1991). Within Dickenson County, rolling knob-and-kettle topography occupies areas near the Des Moines Lobe's western lateral margin while the lobe's more central portions have quite low relief. Most of Dickenson County is under cultivation typical of the Midwestern United States. The area's low relief coupled with extensive agricultural farmland and sparse forest cover offer an ideal validation site for satellites with relatively large pixel sizes, such as the 250 to 1000 m pixels of MODIS.

The first study site, Sunken Lake, is a small enclosed kettle lake adjacent to Big Spirit Lake. As the name implies, Sunken Lake is a local topographic low, protected by fringing trees. While snow had blown off most other lake surfaces over the course of the study period, the surface of this protected lake maintained a thin (~ 3-5 mm) uniform snow layer over most of its surface. This site, while too small to serve as a validation target for MODIS, was well suited to compare snow albedo measured using three different types of pyranometers. Swan Lake, a larger and less protected kettle lake, located approximately 12 km ENE of the town of Spirit Lake was used to assess the accuracy of snow albedo retrievals over a frozen lake covered with patchy snow. Gently rolling farm fields located 5 km east of Spirit Lake last planted in soybeans and corn served as a study site typical of agricultural conditions in the area. All three study sites are located in the rolling typography typical of the western margin of the Des Moines Lobe (Figure 1).

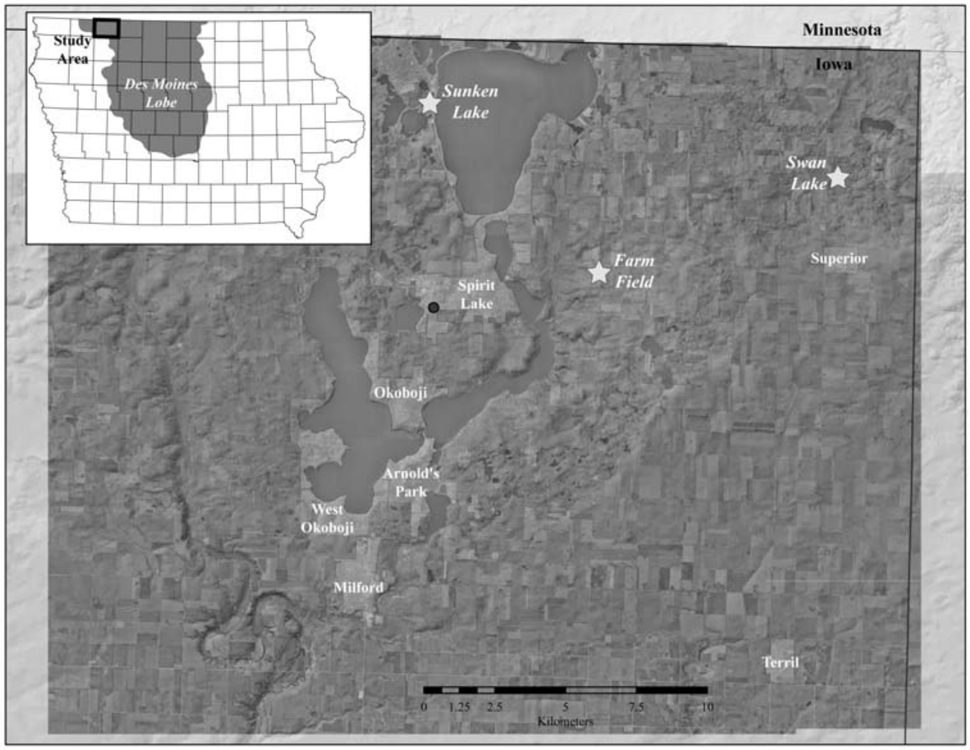

Figure 1: Digital orthophotograph mosaic obtained from the Iowa Geographic Image Map Server illustrating the three studies sites (stars) and surrounding areas of Dickenson County, Iowa. (http://ortho.gis.iastate.edu/).

METEOROLOGICAL CONDITIONS

Comparison of snow albedo retrievals with field measurements requires clear skies, freezing temperatures and snow cover. Hourly meteorological observations made by the FAA-ASOS site (KSPW) at Spencer, Iowa, located approximately 30 km south of the study sites, show that clear skies and freezing temperatures dominated the February 24-28 field campaign period (Figure 2).

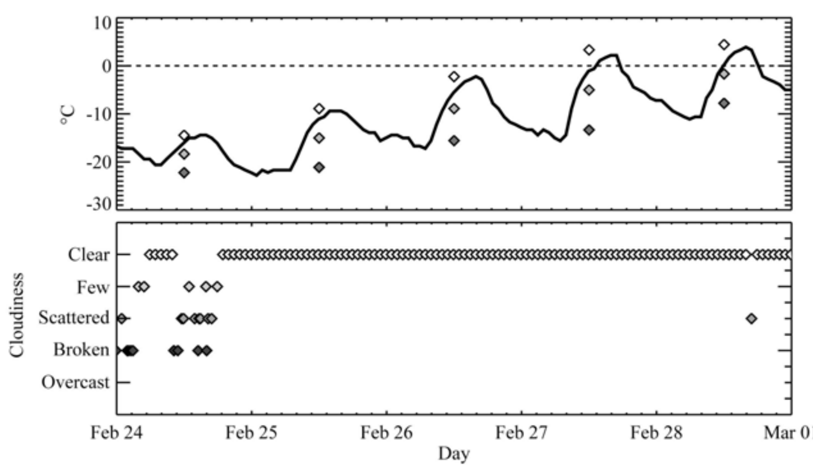

Figure 2: (upper panel) hourly temperatures recorded by the KSWP ASOS station in Spencer, Iowa (solid line) and daily minimum, maximum and mean temperatures made at the Cooperative Observing Station in Spirit Lake (diamonds). (lower panel) hourly cloudiness recorded at Spencer, Iowa.

With the exception of a mid-February snowstorm that deposited 13 cm of snow at the National Weather Service's cooperative station (137859) in Spirit Lake (Figure 3) snowfall for 2002-2003 winter prior to the field campaign was below historical averages. For the state of Iowa as a whole, the winter of 2002-2003 through the end of February ranked as the 6th driest winter in 130 years of record (Hillaker, 2003). Unfortunately above freezing temperatures followed the February 14th precipitation event and by the beginning of the field campaign only a thin patchy snow cover remained.

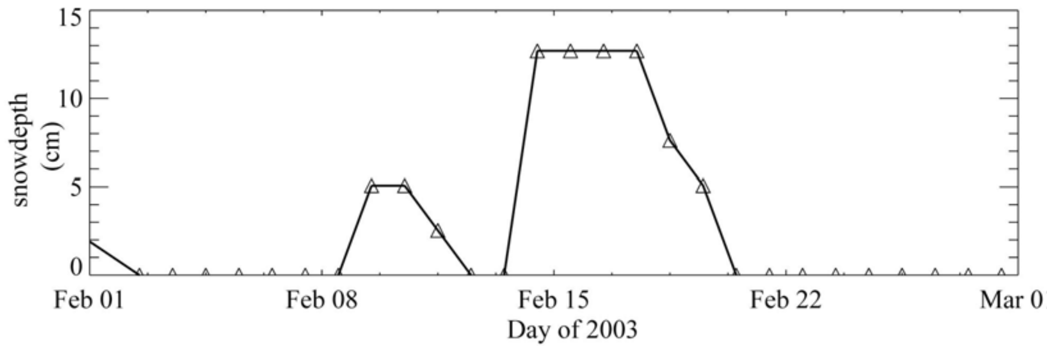

Figure 3: Snow depth (cm) during February 2003 in Spirit Lake Iowa.

METHODS

MODIS-derived albedo

MODIS snow albedo retrievals were calculated using a prototype of the MODIS snow albedo algorithm (Klein *et al*. 2000; Klein and Stroeve, 2002). The prototype is identical to the algorithm used to produce the current beta test albedo products with the one exception. In the prototype albedos are calculated for aggregated 1000 m pixels rather than individual 500 m pixels as in the beta test product. For each day in the period February 24-28, snow albedos were computed for the MODIS Intergerized Sinusoidal tile (h11v04) covering the study area.

Because of the potential for misidentification of clouds and the possibility that pixels with thin patchy snow may not be classified as snow by the MODIS snow-mapping algorithm, snow albedo was computed for all pixels regardless of snow condition and cloud cover. To facilitate comparisons with field observations, the MODIS snow albedo maps and other information were georeferenced to a common map projection (UTM zone 15 projection, NAD 1983 Datum) for ingestion and analysis within a Geographical Information System (GIS).

Albedometer comparison

Pyranometers vary greatly not only in cost and quality, but also in durability. Capturing spatial variation in albedo from *in situ* measurements requires repeated moving of the instruments in cold weather over uneven terrain. While expensive thermocouple based pyranometers are well-suited for sampling at a fixed location, they are less durable and more prone to being damaged by handling than the smaller photovoltaic detectors. A simple assessment of whether less expensive pyranometers can provide short-duration measurements of albedo of suitable quality for validation studies was thus undertaken.

Three albedometers were compared. A Middlteon-EP16 pyrano-albedometer served as the benchmark against which albedometers constructed from two Kipp & Zonen CM3 pyranometers and from two Li-COR LI-200SA pyranometers were compared. The Kipp & Zonen and LI-COR based albedometers were created by mounting uplooking and downlooking sensors on a horizontal bar attached to a photographic tripod (Figure 4). Each pyranometer could be individually leveled.

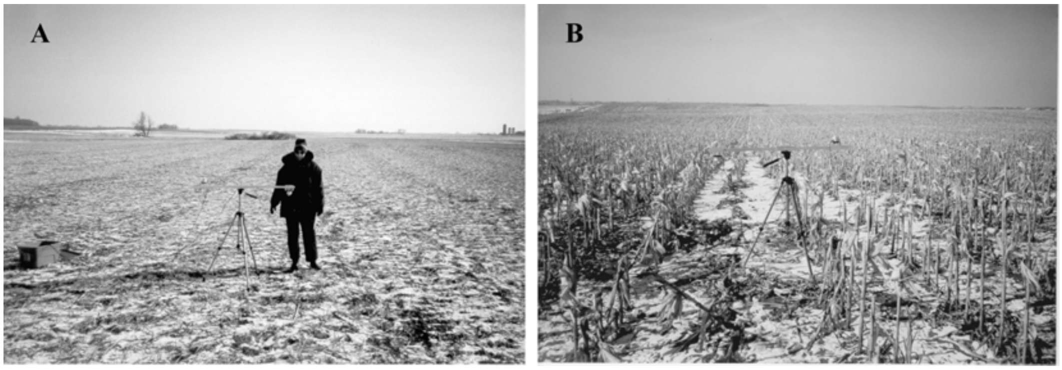

Figure 4: albedometer deployed in a (A) soybean and a (B) corn field.

The Middleton EP16 has a nominal spectral range of 300-3000 nm with 50% of the sampling points falling in the 250-2850 spectral interval. It meets ISO 9060/WMO criteria for a first class pyranometer. The second albedometer consisted of two Kipp & Zonen CM3 pyranometers. The spectral response of these pyranometers covers a similar spectral range (305-2800 nm) as the Middleton EP16. They meet ISO 9060 /WMO criteria for second class pyranometers.

The third albedometer consisted of two LI-COR 200SA pyranometers. These photovoltaic-based sensors cover a limited spectral range (400–1100 nm) and their response is calibrated against first class broadband pyranometers under natural lighting conditions. Therefore, the manufacturer does not recommend that they be used under artificial lighting conditions or for measuring reflected energy (LI-COR, 2003). However, their low cost and durability make them well-suited for studies requiring frequent and repeated redeployment. Fortunately, in the spectral range for which the LI-COR 200SA is sensitive the snow' spectral albedo is both quite uniform and quite high (Henneman and Stefan, 1998) which may make sunlight reflected less of a problem for snow than for other cover types.

On February 28th the three albedometers were deployed within 25 meters of each other on Sunken Lake. An area where the surface appeared visually uniform was selected for analysis. A thin snow cover (~5mm) was present. Snow grain sizes were approximately ~0.5 mm and snow temperatures were at the melting point with some coalescence of grains observed. Snow albedos were recorded from all the three instruments for the period from 10:30 to 13:30 Central Standard Time (CST). The 2-hour period surrounding local noon was selected to minimize the solar zenith angles. During the study period solar zenith angles ranged from 52-63°. Cloud conditions over the study period ranged from clear to partially overcast.

Field Sampling Design

A major study goal was to evaluate the utility of a randomized sampling scheme to construct a field-based and unbiased estimate of snow albedo from *in situ* observations for areas approximating the resolution of a MODIS pixel (500 to 1000 m on a side). The measured albedo for the area can then be compared to snow albedos computed from MODIS observations.

The sampling design had several goals: to be straightforward, to be repeatable at a number of sites and to be executable by one or two individuals. The underlying statistical sampling scheme used was originally developed for environmental monitoring at McMurdo Station, Antarctica, (Kennicutt et al. 1999, Kennicutt et al. 2003) which occupies an area slightly larger than a MODIS pixel. Success using the sampling methodology in Antarctica under similar weather conditions provided confidence that the technique would work and the requisite number of samples could be obtained.

The basic sampling methodology employs a nested spatial sampling design that captures spatial variability in snow albedo at three relevant spatial scales: 10 m, 50 m and 250 m. As illustrated in Figure 5, a 1000 x 1000 m area is subdivided into 16 250x250 m grid cells. A single 250 m grid cell, located at the center of the study area, is then further subdivided into 25 50x50 m cells. Finally, a single 50 m cell is subdivided divided into 25 10x10 m cells. To avoid biases arising from sampling on a uniform grid, the actual sampling point within each cell is randomly determined and albedo measurements are made at these predetermined localities.

Time constraints and changing surface conditions during the observation periods limited the sampling to a 10 meter grid on Swan Lake and a 250 m and 10 m grids on the agricultural fields. The selected grids were chosen because visual analysis of the sites indicated that variability on these scales was important.

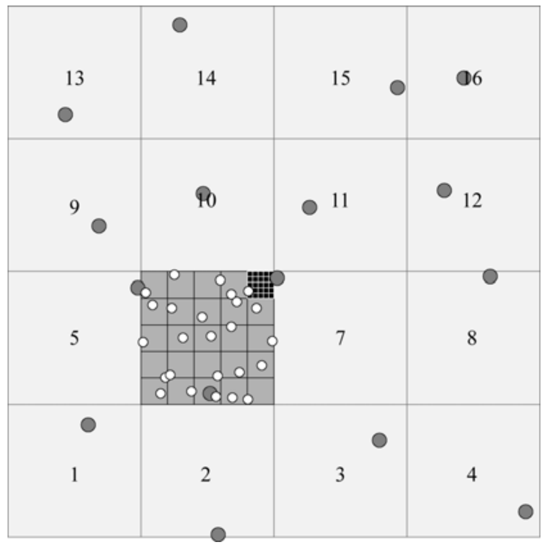

Figure 5: Basic field sampling design with 250 m (light gray), 50 m (medium gray) and 10 m (black) grid cells. The location within each grid cell is random (circles).

Field Measurements

Field sampling was accomplished by navigating to the random sampling point using a handheld Global Positioning System (GPS) unit. The 2-3 meter positioning accuracy of a Wide Area Augmentation System (WAAS) enabled GPS receiver provided adequate geolocation information. Once each site was located, an albedometer was deployed, leveled, and left to record for 3-5 minutes. Average albedos for 10 second intervals during each 3-5 minute sampling period were recorded by a Campbell Scientific CR23X data logger.

Post Processing

An average albedo for each sampling location was calculated from the recorded field observations by first visually analyzing the albedo time series for each location and removing spurious albedos which sometimes occurred at the beginning and end of the sampling interval. From the remaining samples, three measures of central tendency (mean, median and mode) were computed as was the variance and the minimum and maximum albedo for the sampling period. Because of the small scatter in most of the observations, and potential contamination at the beginning and end of the recording periods, the median was the most reliable estimate of central tendency. However, in 80% of the cases the median and mean albedos were within 0.25%.

Interpolation and Areal Averaging.

In order to derive an albedo estimate for the entire site that can be compared to the retrieved MODIS albedo, individual albedo observations were combined into a site average using several different methods. For Swan Lake, only the arithmetic average was computed. For the agricultural fields, a site albedo was calculated by several methods including a simple arithmetic mean, an average weighted by the areal proportions of each landcover type and by using inverse distance weighting (IDW) and kriging spatial interpolation techniques to create site albedo maps.

RESULTS

Albedometer comparison

Over the three hour study period, the albedos recorded on Sunken Lake from the three albedometers were quite comparable (Figure 6). Most importantly the 10 second albedo measurements of the three pyranometers were all found to lie within 3% of each other. As expected, the albedo measured by the Middleton and Kipp & Zonen thermocouple pyranometers were lower than the LI-COR measured albedos as snow's albedo is highest in the visible and near-infrared portions of the spectrum observed by the LI-200SA pyranometers. Henneman and Stefan (1998) noted a similar response between the LI-COR and Kipp & Zonen pyranometers for daily snow albedos. The Middleton EP16 shows small amplitude (~1%) but high frequency (~15 minute) variations in albedo not captured by the other two instruments. The cause of this difference is not known.

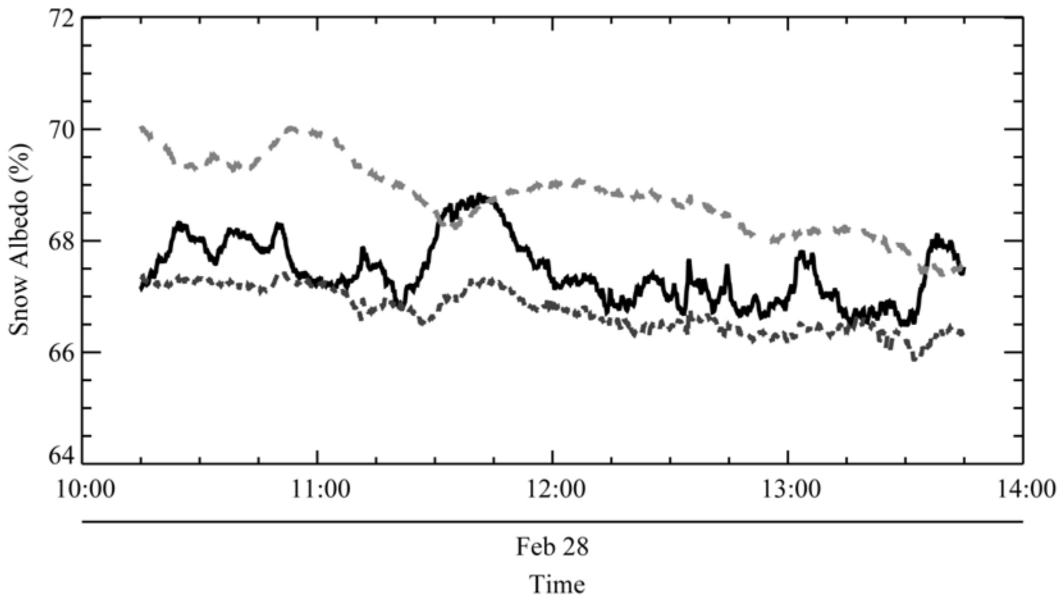

Figure 6: Albedos on Sunken Lake recorded by the Middleton EP16 (solid black line), Kipp & Zonen CM3 (dotted medium gray line) and LI-COR 200SA (dashed light gray line) pyrano-albedometers.

Lake Ice

On February 25th, 25 albedo measurements were made on the lake ice and patchy snow of Swan Lake (Figure 1). Investigations of snow conditions on the late afternoon of February 24th indicated the lakes surface was mostly covered with thin layer of snow. However, sustained winds during the morning of the 25th blew much of the snow cover off of the lake, leaving only patchy snow. These snow patches were typically 1-2 m in the direction transverse to the southerly prevailing wind direction and 3-4 meters in the prevailing wind direction. Snow thickness in these patches varied, but was usually less than 1 cm. Visual inspection showed the greatest variability in albedo on the lake was the interspersion of high albedo snow patches with lower albedo lake ice.

To capture this spatial variability in albedo, it was decided that sampling on a 10 meter grid was most appropriate as it appeared that the patchiness of the snow was fairly uniform across the lake surface and relatively little would be gained by sampling on coarser grids. Therefore, 25 *in situ* snow samples on a 10 m random sampling grid were obtained. Because of the ice surface and high sustained winds, the more durable LI-COR albedometer was employed. One of the 25 samples was subsequently found to be corrupted due to wiring problems.

In addition to the spatial sampling, the Middleton EP16 pyrano-albedometer was deployed in a stationary location at the NE corner of the 10 meter sampling grid (site 25) to assess temporal changes over the course of the study period at a fixed locality. For equal time periods the albedometer was pointed at snow and at lake ice.

In terms of their albedo, the 24 viable random spatial samples clustered into three groups: (1) snow with albedos generally above 55%, (2) lake ice with albedos between 25% and 40% and (3) a few sites suggesting a mix of the snow and lake ice (Figure 7). Because spatial changes in albedo occurred at abrupt boundaries rather varying smoothly over the 50x50 m plot, spatial interpolation was not used to derive a site average albedo. Instead it was assumed that these randomly selected locations were representative of the fractions of snow and lake ice across the entire lake. Thus, the site albedo was taken as the arithmetic mean of the 24 samples (51.2%). The samples' high standard deviation (17.7%) is a product of the high variability in albedo of the lake surface. A simple time-averaging of measurements from the 'stationary' Middleton pyranometer over the study period yielded a similar mean albedo and standard deviation (53.7%±15.2%).

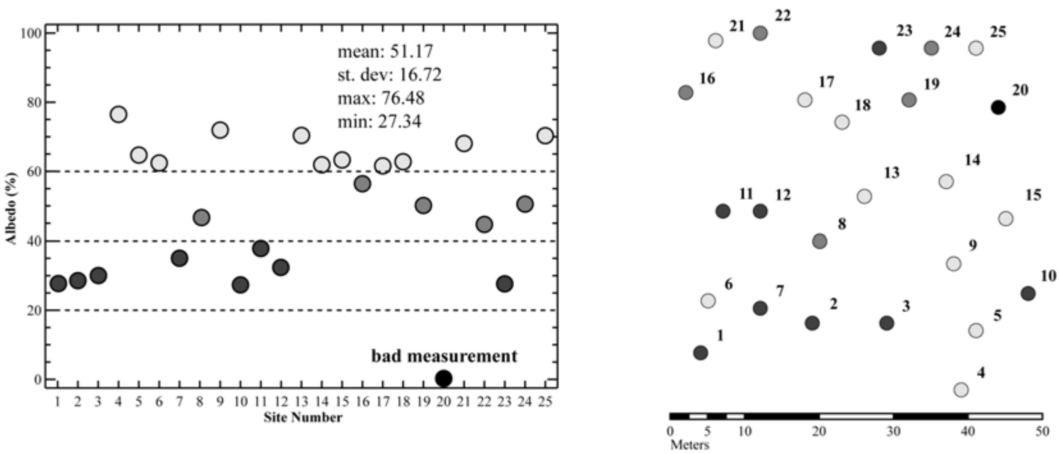

Figure 7: Broadband albedo measurements on Swan Lake by (A) site number and (B) location. The Middleton EP16 albedometer was deployed at site 25.

Examination of MODIS retrievals for the 4 pixels nearest Sunken Lake for February 25th and for the preceding and subsequent days (Table 1) reveals a rapid decrease in albedo over the 3 day period. On February 25th, the MODIS retrieved albedos ranged from 63.7%–65.8%, approximately 10% higher than those measured *in situ* over a small portion of the lake. These MODIS acquisitions that occurred sometime during the period from 10:25 am to 12:10 pm Central Standard Time (CST) and that the albedo of the surface was observed to decrease over the day. Therefore it is perhaps not surprising that MODIS albedo exceeded that measured *in situ*, as many of the *in situ* measurements were made in the afternoon. The rapid decrease in albedo over the lake for the three-day period bracketing the measurement period is also consistent with field observations.

Table 1. MODIS albedos (in percent) for the four pixels surrounding Sunken Lake on three days. The image acquisition period (CST) is also listed.

February 24th		February 25th		February 26th	
88.8	65.8	65.8	63.7	34.7	35.4
81.5	64.5	64.5	65.1	39.1	36.3
9:40-11:05		10:25-12:10		9:30-12:50	

Farm Fields

On February 26th and the morning of February 27th, albedo measurements were made on several agricultural fields encompassing an area approximately 1 km^2 (Figure 8). The fields were rolling and moderate relief (a few 10s of meters). While flatter fields could have been sampled, the gentle relief of this field resulted in it retaining more snow than more exposed sites at the start of the field measurements. While several cover types existed in the 1 km^2 area, the dominant crop from the previous season was soybeans (Table 2). Some corn stubble as well as a low marshy area and a home site were also located in the study site. Such a mixed land use is typical of many regions of the Midwestern United States.

Table 2. Land cover percentages in the study site and breakdown samples collected by land cover type

Cover Type	**Area (m^2)**	**Percent of Total Area**	**Number of Samples**	**Percent of Total Samples**
Corn	160,992	15.3	3	12.5
Grass	11,922	1.1	1	6.3
Marsh	13,335	1.3	1	6.3
Pasture	144,471	13.8	0	0
soybeans	704,938	67.1	11	75.0
Trees	14,900	1.4	0	0
Total	1,050,558		16	

No-till farming practices designed to reduce soil erosion result in considerable crop residue and stubble being left on the fields during the winter, which can have a marked impact on the albedo. In the case of soybeans, no-till practices result in surface with higher albedo than a tilled field and crop stubble approximately 10-20 cm high (Figure 4A). Fields planted in corn have considerably more stubble, typically 60-100 cm in height, with a much rougher surface (Figure 4B). For the cases of patchy snow, this makes soybean fields a preferable validation target.

On February 26th, 16 samples on a 250x250 m grid were collected. Although air temperatures measured at the Spencer airport were never above freezing, melting of the patchy snow was observed to occur, in part due to the low albedo of the area's organic-rich and low albedo soils. On the morning of February 27th, 25 samples were collected on a 10 m grid. As rapid melting was occurring during the sampling and air temperatures were rising, it was decided that further sampling on a 50 m grid would yield no useful information.

Retrieved MODIS albedos (Table 3) show a marked decrease in albedo over three-day period February 25-27, which is consistent with an observed decrease in snow cover. Retrieved MODIS albedos for the four MODIS pixels surrounding the site for February 26th indicate albedos ranging from 41-46% which are 25-30% lower than the previous day.

Table 3. MODIS albedos (in percent) for the four pixels surrounding the agricultural study site on three days. The image acquisition period (CST) is also listed.

February 25th		February 26th		February 27th	
72.7	72.7	40.7	45.8	21.3	16.3
70.7	70.3	45.2	43.9	22.1	17.4
10:25-12:10		9:30-12:50		10:10-13:35	

As detailed above, the 16 *in situ* observations were combined into a single albedo estimate for the study site using several techniques. The resulting albedos are listed in Table 4. The albedo estimates made using the 16 random 250 m samples lie within a fairly narrow range (35.3-38.2%). One example of a derived snow albedo map for the site is illustrated in Figure 9.

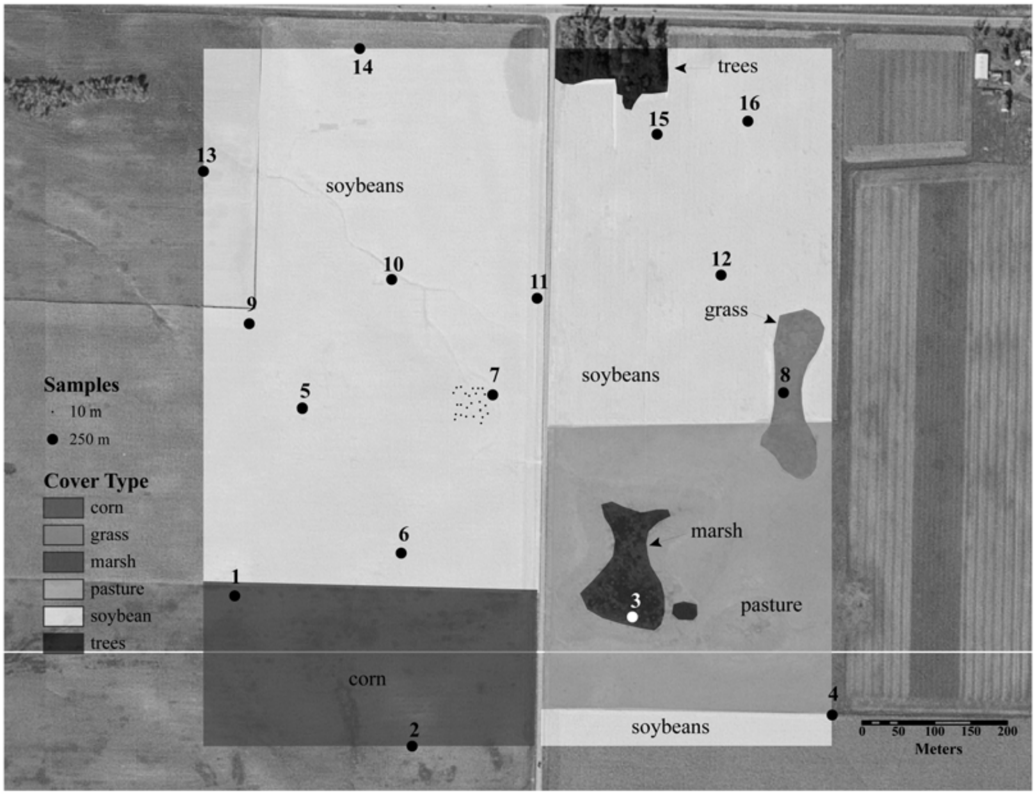

Figure 8: Crop types and 10 m and 250 m sample locations for the agricultural field study site

The time-average of albedo measurements made by the Middleton EP16 pyrano-albedometer over the course of several hours is considerably higher at 43%. This albedometer, which was located in soybean rubble at a fairly typical site (site 7), showed a decrease in albedo over the course of February 26th from 49% before 11:00 to 39% at 15:00. The decrease in albedo at the site over the course of the day is consistent with observed melting over the same period. Decreases in albedo would also be expected at the random sampling sites as well. The discrepancy between the Middleton measurements and the site averaged albedo is not surprising, given that the random site selected for the Middleton instrument was on soybean stubble with a fair amount of snow surrounding it and thus has higher albedo (Figure 9). It does, however, highlight the problem with taking a single site as representative of a larger area.

Table 4. Estimates of site albedo for February 26th using various methods

	Description	**Albedo (%)**
1	Time Average from single site	43.09
2	Average of 16 measurements sites	36.57
3	Average of IDW surface	36.28
4	Average of Kriged Surface	35.43
5	Area Weighted Using only sampled cover types	38.15
6	Area Weighted Using best guess for missing cover types	38.23

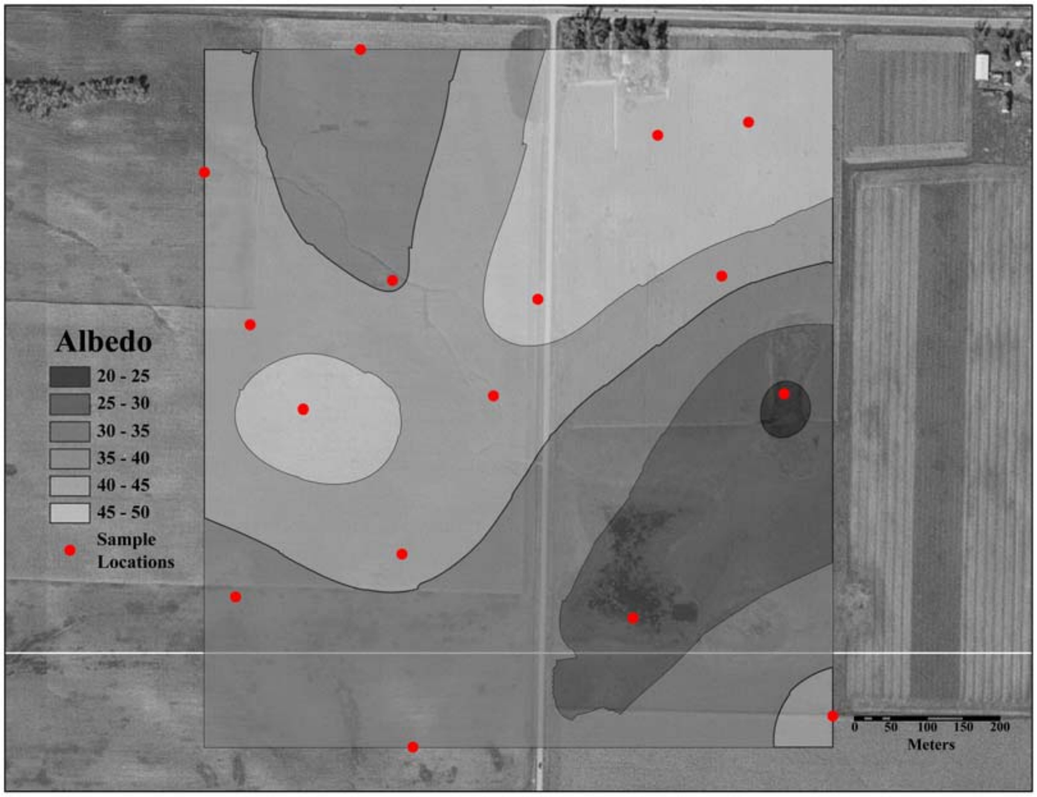

Figure 9: Albedo map of agricultural fields created by kriging of the 16 250 m albedo measurements (dots).

If the methods used to determine an overall site albedo are compared in detail several pertinent points can be highlighted. The first is that the randomized sampling scheme is by design general and does not take into account site specific land cover differences. Therefore, in this particular set of random localities one substantial land cover present within the study site, pasture which accounted for approximately 14% of the area was not sampled. However, two land covers present in small amounts, some tall grass and reedy vegetation occupying topographic depressions were. However, overall the randomized sampling scheme did capture differences in albedo within soybeans, the major vegetation type as exemplified by random sampling sites falling near fences and drainage channels, both of which tend to accumulate more snow than more exposed portions of the fields.

As can be seen in Table 4, the three albedo estimates (simple averaging, inverse distance weighting and kriging), which do not attempt to take landcover differences into account, produce albedo estimates lying within a narrow range (35.4-36.6%). The two methods that attempt to take landcover into consideration produce slightly higher albedo estimates (38.2%). In these two methods, the study site is broken down into a series of parcels with different cover type and/or ownership. The albedo of each parcel is determined from the measurements falling within it. Two approaches were used. In the first parcels without measurements were ignored in the calculation; in the second unsampled parcels were assigned the albedo of the most similar sampled cover.

All estimates of albedo made from *in situ* observations are approximately 10% lower than those retrieved by satellite. This is similar to the situation on Swan Lake for the previous day. However, again there is a time discrepancy between the period of satellite observations and the *in situ* measurements as the satellite acquisition times were between 9:30-12:50 CST while *in situ* observations continued later into the afternoon during which time melting was occurring.

The 25 random samples collected on a 10 m grid in soybean stubble on the morning of February 27th, indicate the albedo of at least a small portion of the study site had decreased markedly since the following day. As can be seen in Table 5, simple averaging, kriging and IDW result in quite similar albedo estimate (23.6-24.2%). The MODIS retrievals for the four pixels surrounding the study site on this day show a range from 16.3-22%). It would appear that the MODIS and *in situ* observations, albeit for a small area are quite comparable, especially as it was noted on the previous day that areas covered by soybean residue typically have higher albedo than other cover types.

Table 5. Estimates of site albedo for February 27th using various methods

	Description	Albedo (%)
1	Average of 16 measurements sites	24.2
2	Average of IDW surface	23.6
3	Average of Kriged Surface	23.8

CONCLUSIONS

From this preliminary study, several pertinent conclusions can be drawn. First, for the patchy snow conditions encountered in this field study, inexpensive LI-COR pyranometers can be reasonably be employed for albedo determination. The small differences in snow albedo measured between the LI-COR albedometer and those employing more expensive thermocouple pyranometers are easily overwhelmed by the large differences in albedo between land cover types and attendant uncertainties in any interpolation method. However, LI-COR based albedometers may not be of sufficient quality to capture subtle differences in the snow albedo across more uniform snow-covered surfaces.

While determining the albedo of thin patchy snow cover sites is difficult, the methodology used here does produce reasonable estimates of the albedo of areas comparable in size to 1 km^2 MODIS pixels. Thus these measurements are useful in validating the snow albedos retrieved from MODIS and other low resolution environmental satellites.

Compared to other land cover types, measuring the albedo of snow-covered sites, especially when the snow cover is patchy and melting, is difficult. Not only is there large variability in albedo across the footprint of low resolution satellites, the albedo of the site can vary rapidly during the time field measurements are made.

Therefore, some modifications to the developed methodology are required. Of most importance is minimizing the length of time required to make the albedo measurements. This can be accomplished in two ways. First even over flat terrain, locating the sampling site and transiting between sites requires the most time. Thus locating the sites prior to collecting albedos can cut the sampling time considerably. Secondly, the actual albedo recording period at each site can be shortened to 2 minutes with no degradation of the recorded albedo.

Despite problems and uncertainties in the field measurements, the retrieved MODIS albedos over the study period were consistent both in magnitude and temporal trends with conditions observed during the February 24-28 field campaign. On February 25th and 26th, MODIS retrieved albedos were approximately 10% higher than those observed on a frozen lake and farm fields typical of the upper Midwestern United States. However, during each day when field measurements were collected, albedo time series also show a decrease. Thus the actual *in situ* albedo may have been higher earlier in the day during which the MODIS acquisitions were made. Limited sampling on the 27th show MODIS retrievals to be within 10% of those measured, albeit over a small area in a single cover type. Therefore these preliminary field measurements suggest that MODIS snow albedos are reasonable for the patchy snow conditions at these study sites over the study period.

ACKNOWLEDGEMENTS

The author would like to thank Dr. Carl E. and Sharon Klein for their help with field measurements and for Greg Krieger for constructing the albedometer stands. This research was partially funded by NASA grant NAG5-11847.

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