Satellite-Observed Reflectance of Snow and Clouds

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ABSTRACT

The effects of snow and cloud cover on bidirectional reflectance were examined using visible radiation (0.5–0.7 μm) data measured by NOAA polar orbiting satellites between June 1974 and February 1978. Reflectances resulting from different cloud/snow cover conditions were compared using Northern Hemisphere snow cover maps, surface weather charts, satellite photos and data on land surface types. This was done for the prevalent surface types found in regions which, at certain times during the Northern Hemisphere winter, showed marked interannual variations in snow cover.

None of the cases studied showed that concurrent cloud and snow cover produced significantly different reflectances than cloud cover alone. Cloud cover alone was found to yield higher reflectances (~0.62) than snow cover alone, with the difference being greatest over forested areas. Clear-sky reflectances over farming and grazing lands [snow (0.45), no snow (0.15)] were found to be significantly higher than those over forested regions [snow (0.33), no snow (0.11)]. Variations in satellite zenith angle were not found to produce significant effects in most cases studied. Local viewing times at high latitudes for the polar orbiting satellites were found to vary from 0800 to as late as 1200 LST.

1. Introduction

Reasonably accurate measurements of planetary albedo were first obtained with the Nimbus II meteorological satellite, which operated from 16 May to 28 July 1966. Nimbus II was the first satellite to measure the radiation balance over the entire globe due to its nearly polar, sun-synchronous orbit (Raschke, 1968). Since then increases in satellite operational lifetime, along with improvements in the resolution of radiometers, have led to larger and more accurate compilations of radiation budget parameters, including planetary albedo. Despite this, there have been relatively few studies to date of satellite data that have examined the nature and variability of planetary albedo (Henderson-Sellers and Wilson, 1982).

The purpose of this study is to add to the knowledge of the effects of snow and cloud cover on planetary albedo. These effects have important applications in fields of study such as snow/albedo and cloud feedbacks in climate models and snow and cloud detection from satellites. Because the satellite data we use are measured only in visible wavelengths (0.5–0.7 μm) and because only a small range of relative azimuth angles were available and very large satellite viewing angles were unavailable, we present measurements of a particular range of values of the bidirectional reflectance function R (Warren, 1982) rather than comprehensive broadband planetary albedo measurements. In order to transform our measurements into spectral albedo, they would have to be integrated over all reflection angles. Because we find virtually no dependence on viewing zenith angle, however, if azimuth angle dependence is small, then the surfaces we viewed can be assumed to be isotropic and the values we present would represent planetary spectral albedo for the range of solar zenith angles studied. We will use the term "reflectance" in this paper to mean the top-of-the-atmosphere (planetary) visible wavelength value of R for the relative azimuth angles, viewing angles and solar zenith angles indicated. Although Taylor and Stowe (1984) present planetary albedo values and R for snow-covered ice caps, the measurements presented here are the first over seasonally snow-covered land surfaces.

We used observations obtained by NOAA polar orbiting satellites between June 1974, and February 1978 to examine reflectance for conditions of: 1) overcast skies with snow cover present, 2) overcast skies with no snow cover, 3) clear skies with snow cover present and 4) clear skies with no snow cover. These conditions were examined in conjunction with the surface types: 1) coniferous forest, 2) arable and mixed farming lands and 3) grazing lands, these being selected due to their prevalence in the regions chosen for study. Preliminary results were presented by Kaiser and Robock (1984).

2. Data

The NOAA 2, 3, 4, and 5 satellites which obtained the observations used in this study were Improved TI-

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ROS Operational Satellites. A comprehensive description of these satellites is given by Fortuna and Hambrick (1974). Orbital and radiometric characteristics of the satellites resulted in any given point on the earth being viewed at least twice daily; however, only one reflectance value per day was archived. The satellite viewing angle associated with each observation changed from day to day as did the viewing time.

For Northern Hemisphere midlatitudes the viewing time typically ranged from 0800 to 1200 local standard time (LST). It was found that the LST of observed points in the midlatitudes of the Northern Hemisphere is almost always later than 0900 LST, which has been quoted by many authors, e.g., Briegleb and Ramanathan (1982), as being the viewing time of the NOAA satellites. The viewing time is generally later as the latitude increases, being on the order of 1030 LST for latitudes approaching 60°N and occasionally even as late as 1200 LST. This characteristic is due to the inclination of the satellites' orbit with respect to the earth's axis; it actually was an aid in this study as it produced smaller solar zenith angles in the more northerly latitudes than would the earlier viewing time. Due to daily shifts in the satellite orbit with respect to a given location, viewing times were found to vary from day to day, commonly by at least one hour, introducing variations in solar zenith angle on the order of 5° for midlatitudes during winter. Knowledge of the satellite orbital position from which archived reflectance values were obtained allows the satellite viewing angle, solar zenith angle and time of day associated with each observation to be obtained. Methods of determining these parameters are described in Fortuna and Hambrick (1974) and Ruff and Gruber (1975).

Details regarding the compilation of data sets from the NOAA satellite observations are given by Gruber (1977). Reflectance data were initially stored on high resolution Northern and Southern Hemisphere grids. The number of data points was then reduced by averaging subsets of each grid to form 125 × 125 element arrays aligned with the National Meteorological Center polar stereographic base map. A global 2½° latitude by 2½° longitude array of reflectance values was produced by bilinearly interpolating between the four array elements surrounding each latitude–longitude intersection.

Cloud cover was determined from surface weather charts, available every 3 hours in the Western Hemisphere (WH) and every 6 hours in the Eastern Hemisphere. These charts were supplemented with geostationary satellite images over the WH. Even though it is difficult operationally to distinguish cloud cover from snow and ice, a trained observer can usually distinguish cloud cover by making use of synoptic knowledge, visual recognition of the typical pattern made by clouds, and comparisons of the time evolution of the scenes.

Northern Hemisphere weekly snow and ice cover charts were used to identify regions that showed marked interannual variations in snow cover. These charts have been prepared since November 1966 by the Synoptic Analysis Branch of the National Environmental Satellite Service (now NESDIS) and are described by Matson and Wiesnet (1981). Special digitized versions of the charts (Dewey and Heim, 1981) were used to compare snow cover from the same week in different years.

3. Procedure

In order to isolate the four types of sky and snow conditions previously listed, snow cover extent for each week of the year was compared across all years to identify areas with the largest interannual variations. Since the reflectance of clouds and earth surfaces is often dependent upon viewing angle (Taylor and Stowe, 1984) and the albedo is dependent on solar zenith angle (Fig. 6.12, Paltridge and Platt, 1976), it is important to study either these dependencies or try to eliminate them. Although large variations in satellite viewing angle were impossible to avoid, due to orbital factors, the foregoing procedure did help to minimize variations in solar zenith angle, which ranged from 65° to 75°, and at the same time helped ensure similar vegetative states.

The geographical regions chosen for study are shown in Fig. 1. Table 1 lists the predominant surface types

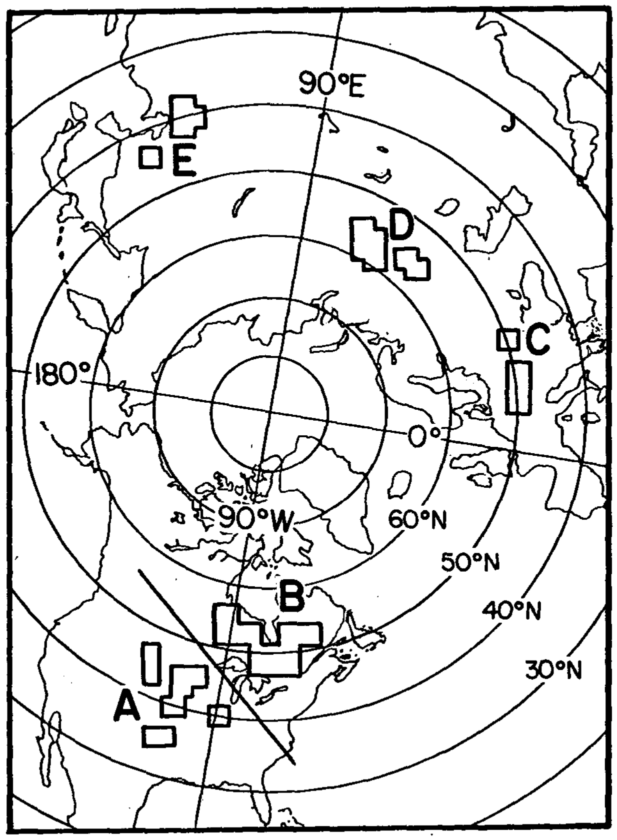

FIG. 1. Map showing the regions chosen for study. (See text and Table 1)

TABLE 1. Surface types and snow-covered/snow-free dates of the regions studied. See Fig. 1 for location of regions A–E.

Region	Surface types*	Dates when snow-covered	Dates when snow-free
A	Grazing/farming	12–18 February 1978	27 October–24 November 1976 14–20 February 1977
B	Coniferous forest	27 October–25 November 1976 19–25 November 1977	27 October–18 November 1977
C	Grazing/farming	12–18 February 1978	14–20 February 1977
D	Grazing/farming	27 October–14 November 1976	27 October–6 November 1974
E	Grazing/farming	12–18 February 1978	14–20 February 1977

* Source: *Oxford World Atlas,* Oxford University, 1973, 190 pp.

found in these areas and the approximate periods when each was snow covered and snow free. Other investigators (e.g., Kung *et al.,* 1964), have shown farming and grazing lands to have similar albedos. Statistical tests performed in this study for snow-covered and snow-free conditions verified this similarity, allowing these two surface types to be grouped together.

An original objective of this work was to study planetary albedo over a wider range of surface types, including deciduous forest and mixed coniferous and deciduous forest. Most areas of deciduous forest, however, were found to be too small for the resolution of the reflectance data set. The same was found to be true for areas of mixed forest, which were found generally in the higher latitudes of the western Soviet Union. In addition, study of these locations would have yielded solar zenith angles > 75° which may produce unreliable radiometer measurements (Henderson-Sellers and Wilson, 1982). Also, few mixed forest regions were found for clear sky conditions. The persistent cloudiness was found to coincide with the approximate position of the wintertime polar front in the western Soviet Union.

In order to understand the influence of clouds on planetary albedo, it will be necessary to do a comprehensive study incorporating all possible combinations of cloud types and fractional cover. Such a comprehensive investigation is beyond the scope of this study, because we did not have enough cases to determine the effects of all cloud combinations with and without the presence of snow. As a first step in the solution of this problem, we decided to limit our data set to cases of completely clear and completely overcast conditions. The only type of overcast condition not included in samples was that comprised of strictly cirrus clouds. The relative thickness of these clouds could not be determined since WMO high level cloud codes do not adequately describe them in terms of transparency. This factor is important, as various types of cirriform clouds have been found to result in widely varying planetary albedos (Henderson-Sellers and Wilson, 1982). The WMO coding of midlevel clouds does, however, denote relative transparency, allowing semi-transparent (less reflective) clouds to be identified and thus not included in samples. Therefore, only overcast conditions resulting from a combination of low, middle or high level clouds, or low or middle clouds alone were studied.

4. Results

Four reflectance data sets, one for each of the above sky/snow cover categories, were assembled for each of the two surface types, making eight data sets altogether. They were assigned three letter acronyms, with the letters having meanings as follows: F—forest, G—grazing, O—overcast, C—clear, S—snow cover, N—no snow cover. Statistics for each sample are presented in Table 2. A standard *t*-test was performed on various pairs of samples to find if the mean reflectances of samples were significantly different.

There are three varying factors involved in studying the eight reflectance samples assembled here: a) surface type, b) snow cover and c) cloudiness. The effects of each will be discussed separately, followed by a discussion of satellite viewing geometry effects and comparisons to previous measurements of surface albedo.

a. *Surface type*

Using the *t*-test to compare the FCN and GCN samples showed their respective means to be significantly different at the 0.01 confidence level, indicating that coniferous forest with no snow cover has a significantly lower reflectance than grazing and farming lands with no snow cover. This has been found by other investigators (e.g., Kung *et al.,* 1964) for surface albedo measurements. The means of the FCS and GCS samples were also significantly different, showing snow-covered grazing and farming lands to be brighter than snow-covered coniferous forest. This result is expected due to the more pronounced blanketing effect of the snow over fields and pastures. An example of this can be seen quite well in the cover photograph accompanying Kukla and Brown (1982).

For overcast conditions, the FOS and GOS mean reflectances were not found to differ significantly. This

TABLE 2. Reflectance: statistics from the different cloud cover, snow cover, and surface type combinations.*

	Code	Mean reflectance	Standard deviation	Number of observations
		Forest		
Overcast				
Snow	FOS	0.62	0.13	55
No Snow	FON	0.64	0.11	103
Clear				
Snow	FCS	0.33 (0.35)	0.09	42
No Snow	FCN	0.11 (0.04)	0.03	30
		Grazing and Farming		
Overcast				
Snow	GOS	0.61	0.08	41
		0.59†	0.09†	54†
No Snow	GON	0.61	0.12	26
		0.54†	0.15†	38†
Clear				
Snow	GCS	0.45 (0.53)	0.12	30
No Snow	GCN	0.15 (0.11)	0.03	37

* Values in parentheses are clear-sky surface albedos resulting from substituting the reflectance values in the relationship derived by Chen and Ohring (1984). See text for explanation of three letter codes.

† Values resulting from the inclusion of European observations. (see text)

was also the case for the FON and GON samples, implying that with or without snow cover, when skies are overcast grazing/farming lands and coniferous forest do not yield significant differences in reflectance.

b. Snow cover

The presence of snow cover increased the clear-sky reflectance significantly for both surface types. While this was certainly to be expected over grazing and farming lands, some studies have shown that this may not necessarily be the case over coniferous forest. Kukla and Robinson (1980), for example, noted that many investigators have found the albedo of coniferous forests with even 30 cm or more of snow on the ground to be only a few percent higher than in summertime. This discrepancy can be explained by the limited spectral range of our observations, to be discussed (Section 4e).

It is interesting to note that even though the spectral range used here (0.5–0.7 μm) may tend to overestimate albedo over snow-covered areas (Wiscombe and Warren, 1980), the mean value found over farming and grazing lands (0.45), for example, was still far below that found by Taylor and Stowe (1984) over the Greenland and Antarctic icecaps (0.73) for similar solar zenith angles. This is most likely due to a combination of factors, such as protruding surface features, older snow cover and impurities deposited on the snow as a result of human activities.

For complete cloud cover, no significant difference was found between the FOS and FON samples or between the GOS and GON samples, indicating that under overcast skies, the presence of snow cover on either of these surfaces does not significantly increase the reflectance. While the difference between the GOS and GON standard deviations was not found to be statistically significant, the wider spread of the GON data may hint at the occurrence of snow-free surfaces showing through thin spots or undetected openings in the clouds. European data (region C, Fig. 1) were not included in the GOS and GON samples as their means (0.51—GOS, 0.40—GON) were significantly lower than those from the other regions. This was most likely due to including partly cloudy cases in the observations, as viewing times were close to 09 GMT, allowing sky conditions to be different from the overcast we observed on the 06 and 12 GMT maps. While it was not possible to determine the exact nature of the cloudiness, the fact that the European GOS and GON means were significantly different from each other may show an effect of snow cover under partially cloudy skies.

c. Cloudiness

All four overcast samples had significantly higher mean reflectance values than even the brightest of the clear-sky samples (snow-covered grazing and farming lands). However, several GCS observations were as high as the mean overcast reflectances, most likely being associated with very fresh snow cover.

d. Viewing geometry effects

Plots of reflectance versus satellite zenith angle for all eight cases are shown in Figs. 2–9. Positive angles

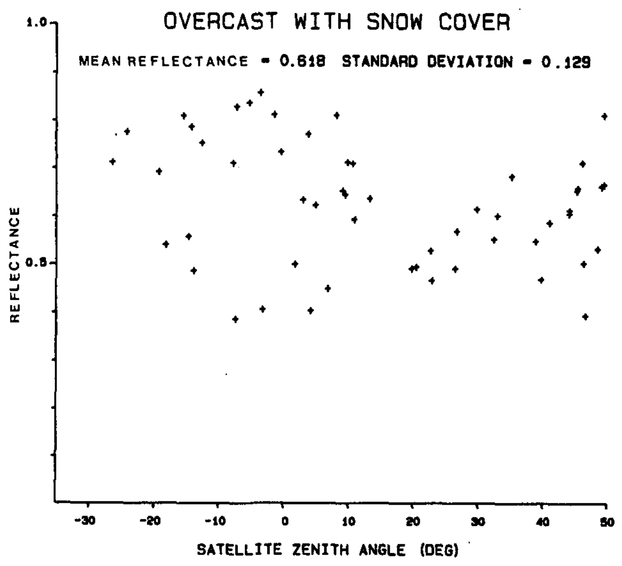

FIG. 2. Plot of reflectance vs. satellite zenith angle for coniferous forest with overcast skies and snow cover present.

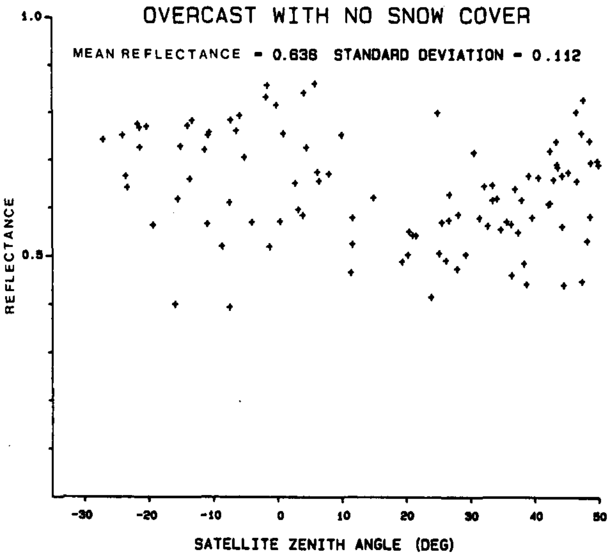

FIG. 3. As in Fig. 2 for coniferous forest but no snow cover present.

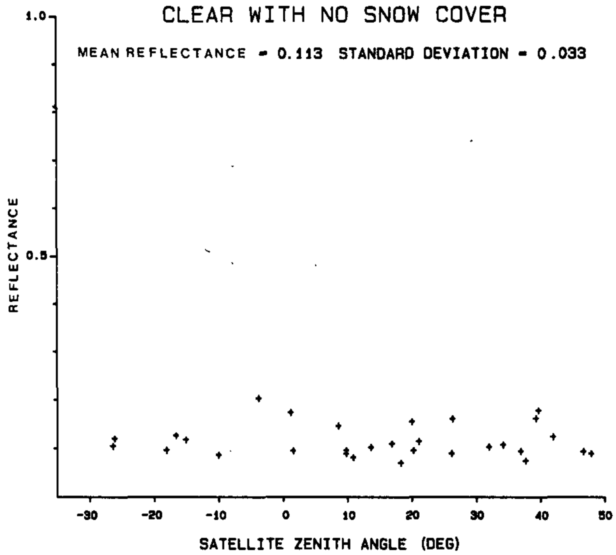

FIG. 5. As in Fig. 2 for coniferous forest but for clear skies and no snow cover.

relate to forward scattering of reflected solar radiation at relative azimuths between approximately 135° and 150° from the sun, while negative ones indicate backscattering at relative azimuths ranging from about −30° to −40° from the sun. These small variations in relative azimuth prompted us to focus on variations in satellite zenith angle.

Statistical tests performed on all samples showed reflectance to be dependent on satellite zenith angle only for the FOS and FON samples, a relationship being apparent for satellite zenith angles greater than about +20° (forward scattering conditions). This effect of increased reflectance with increasing satellite zenith angle in the forward-scattering direction, is qualitatively similar to findings of Taylor and Stowe (1984). The reason for not finding such a relationship in the GOS and GON samples may lie in the nature of the overcast. Cloud types coded on surface weather maps, as well as those observed with visible and infrared GOES imagery, showed a more consistent type of cloudiness over the forested regions in eastern Canada, mainly consisting of stratocumulus clouds. The relative uniformity of the clouds may have allowed a true angular dependence of the measured reflectances to show up. Cloud types over the grazing/farming regions were more variable, often showing overcast conditions to consist of

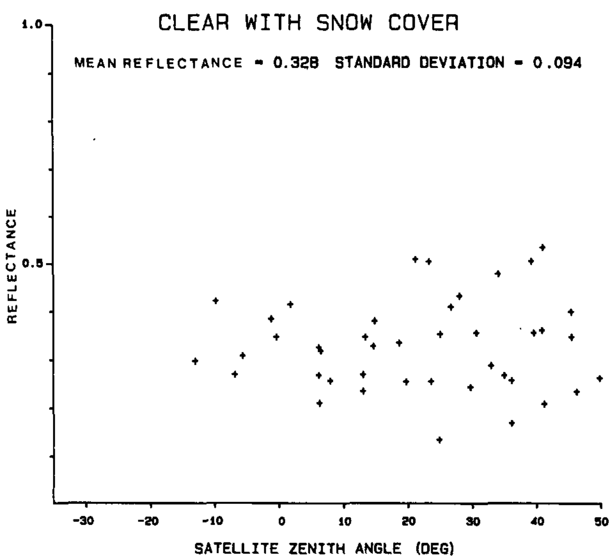

FIG. 4. As in Fig. 2 for coniferous forest but for clear skies.

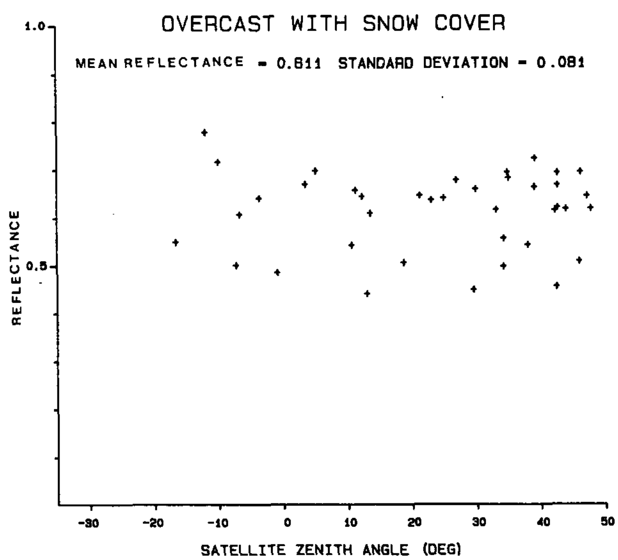

FIG. 6. As in Fig. 2 but for grazing/farming surface type.

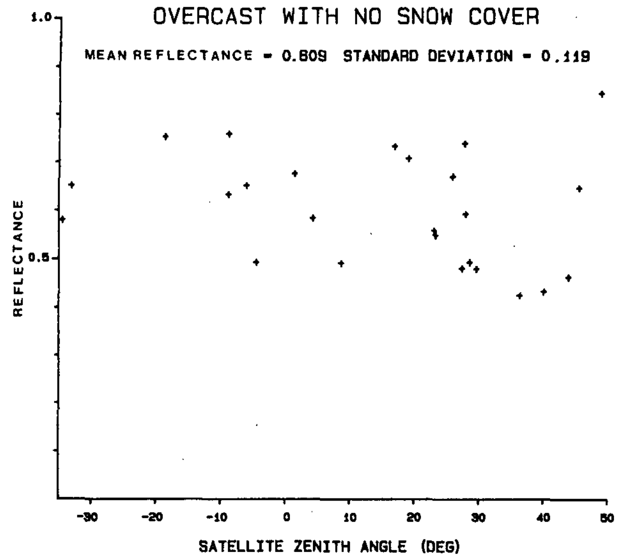

FIG. 7. As in Fig. 3 but for grazing/farming surface type.

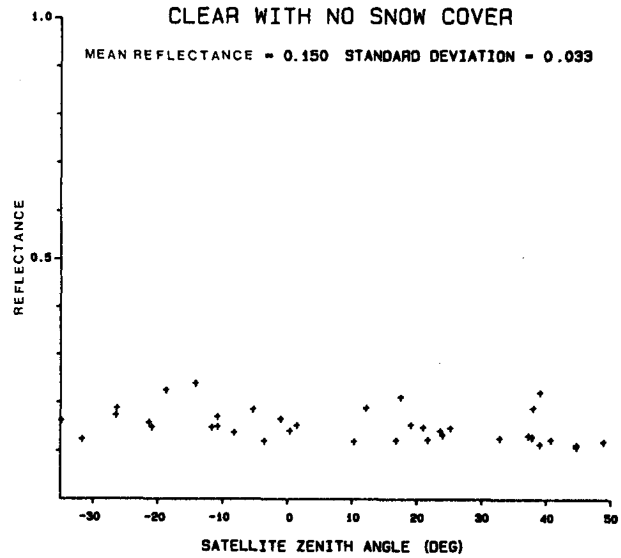

FIG. 9. As in Fig. 5 but for grazing/farming surface type.

clouds at different levels. This variability perhaps introduced a randomness to the data points that would have been smaller for more uniform cloud conditions. The lack of satellite zenith angle dependencies for the clear-sky conditions examined also parallels the findings of Taylor and Stowe (1984) for satellite zenith angles less than about 50° (the maximum angle associated with the observations used here).

e. Surface albedo comparison

Also included in Table 2 are surface albedos obtained by substituting the observed average clear-sky reflectances in the relationship derived by Chen and Ohring

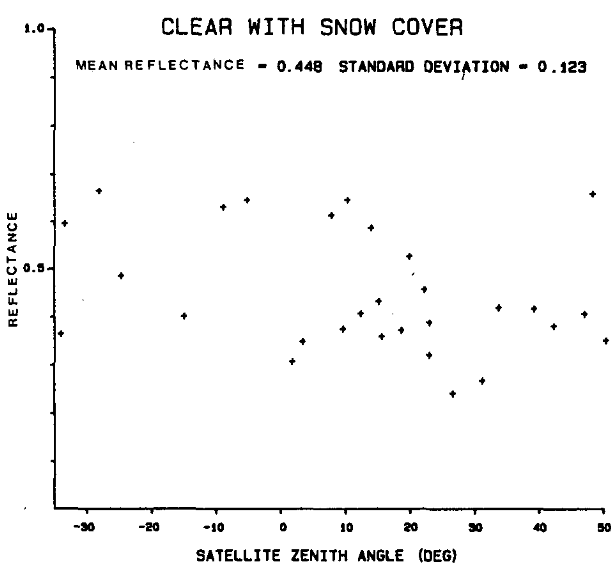

FIG. 8. As in Fig. 4 but for grazing/farming surface type.

[(1984), their Eq. (6)] and choosing the parameters from their Table 2 to correspond to the actual solar zenith angle (72.5° for forest and 68° for grazing/farming). The resulting values of surface albedo for the four clear sky situations studied here agree fairly well with previous measurements, but the spectral range of each measurement must be carefully considered in the comparison.

Chen and Ohring used the same NOAA scanning radiometer narrow band visible (0.5–0.7 μm) measurements that we used to derive equivalent broadband surface albedos, claiming that the results of Briegleb and Ramanathan (1982) supported this procedure. Briegleb and Ramanathan did find that the narrow band visible measurements agreed with the broadband values when averaged over all surface types, but for the specific types used in our study, we must consider the spectral dependence of the albedo of each separately. For all types of vegetation, the visible albedo is much lower than the near-IR value (Rind, 1984), with the broadband average, therefore, being higher than the visible. For snow, on the other hand, the visible albedo is much higher than the near-IR (Wiscombe and Warren, 1980). The contrasts that we found between snow-covered and snow-free surfaces would therefore be less when consideration is made for the full spectrum.

For farming and grazing lands, Kung *et al.* (1964) reported the March snow-free/snow-covered broadband surface albedos of cornfields (a prevalent surface in region A of Fig. 1) in Iowa to be approximately 0.13 and 0.50, respectively. Our average observed values when substituted in Chen and Ohring's (1984) Eq. (6) yield values of 0.11 and 0.53, respectively. Rind (1984) reported visible band surface albedos of 0.09–0.11 for snow-free grass and shrubland for autumn and winter.

For forests Griggs (1968) reports a range of approximately 0.07–0.09 (location of forest not given) while Kung *et al.* (1964) report a range of about 0.14–0.16 over the area encompassed by region B in Fig. 1, both for broadband surface albedo, while Rind (1984) reports 0.05–0.10 for autumn and winter visible surface albedo. The Chen and Ohring (1984) relationship yields a surface albedo of 0.04 when used with our average reflectance over snow-free coniferous forest. The derived surface albedo found here for snow-covered coniferous forest (0.35) seems realistic when compared with values from Kung *et al.* (1964) who report a range of 0.37–0.55 within region B in Fig. 1.

5. Conclusions

Top-of-the-atmosphere bidirectional visible band reflectances, measured by NOAA polar orbiting satellites, were examined for eight different surface type/cloud cover/snow cover conditions. It was found that concurrent cloud and snow cover do not produce higher reflectance values than does cloud cover alone. This is found to be the case over both grazing/farming lands and coniferous forest. This study may be considered a limiting case due to the selection of cloud conditions (thick, complete overcast). The selection of optically thinner clouds, e.g., cirrus alone, or partially cloudy conditions, may reveal significant differences in reflectance over certain snow-covered/snow-free terrain. All overcast conditions examined were found to produce higher reflectances than clear-sky, snow-covered conditions.

Clear-sky reflectances over snow-covered grazing/farming lands were found to be significantly higher than those over snow-covered coniferous forests. The same relationship was found for the clear-sky, snow-free conditions. Snow-covered forests and grazing/farming lands had significantly higher clear-sky reflectances than snow-free surfaces. While the visible band is not ideal for snow measurement because of the confusion caused by clouds, in clear sky cases, because of the spectral dependence of snow and vegetation albedos, snow can be more easily detected than with broadband measurements.

Possible effects of satellite zenith angle upon measured reflectances were only found for overcast conditions in which the clouds were observed to be fairly homogeneous. Since in virtually all cases studied, the surfaces did not display any angular dependence of the reflectivities, the measurements presented here can be considered as representative of planetary albedos in the visible band. More such measurements will have to be made in the future before the complete broadband reflectance properties of snow and clouds are known for all conditions.

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