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Human-Induced Changes in Winter Surface Albedo

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With 1 Figure

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Summary

The surface albedo of snow-covered deforested portions of the United States is approximately twice as high as when naturally vegetated. Moderate increases of up to about 0.20 are found for snow-covered farmland developed from former medium and tall grasslands. These changes may be considered representative of other populated regions in the middle latitudes. As a result, the winter surface albedo and, in turn, boundary-layer climates in these zones have become considerably more sensitive to the presence and duration of snow cover. Results are obtained from two models using satellite derived surface brightness fields, aerial albedo measurements of relatively undisturbed sites representative of past vegetation and global land-cover data sets. They refer to a block between 38° and 43°N latitude and 71° and 105°W longitude.

Zusammenfassung

Anthropogene Veränderungen der winterlichen Albedo

Die Albedo der schneebedeckten, entwaldeten Teilen der U.S.A. ist etwa doppelt so hoch wie bei natürlicher Vegetation. Auch bei schneebedecktem Ackerland erhöht sie sich bis zu ca. 20% gegenüber den früheren Grasländern. Diese Veränderungen dürften für andere bewohnte Gebiete der mittleren Breiten repräsentativ sein. Damit ist die winterliche Albedo in diesen Gebieten und mit ihr das Klima der atmosphärischen Grenzschicht abhängiger vom Vorhandensein und von der Dauer einer Schneedecke. Die Ergebnisse stammen von zwei Modellen, die beruhen auf: Satellitendaten der Oberflächenhelligkeit, Luftaufnahmen der Albedo in relativ ungestörten Gebieten, die für die frühere Vegetation typisch sind und Daten der globalen Landbedeckung. Sie beziehen sich auf das Gebiet zwischen 38–43° nördlicher Breite und 71–105° westlicher Länge.

1. Introduction

Previous studies regarding human-induced albedo change have been concerned primarily with increases of surface albedo resulting from desertification and tropical deforestation [1–4]. Results from climate-model studies indicate that such changes affect atmospheric circulation, leading to lower precipitation [5–8] and lower surface temperatures [4, 9, 10, 11]. Human-induced changes in surface albedo of the middle latitudes have received little attention, despite their potential role in historic climate change. Due to snow-ice/albedo feedbacks, human-induced increases of CO_2 and other "greenhouse" gases and the potential consequences of nuclear war are expected to have a major climatic impact on seasonally snow covered regions, which include much of the northern middle latitudes [12, 13].

We report here the results of a regional-scale study in which the anthropogenic impact on winter surface albedo was estimated in a portion of the United States between 71–105°W and 38–43°N (Fig. 1). Two models are employed in the estimate of past and present albedo distributions and their results compared. In the first, referred to as ANTHRO1, the mean albedo for each ecosystem type in the study area is derived from Defense Meteorological Satellite Program (DMSP) imagery brightness fields analyzed over all seasonally snow-covered lands in the Northern Hemisphere. Surface albedo distributions are constructed by applying the so obtained mean ecosystem albedo values to both past and present land-cover distributions.

In the second model, ANTHRO2, aerial albedo measurements of selected undisturbed snow covered sites, representative of past U.S. natural ecosystems, are applied to the distribution of past land-cover; present albedo was derived from DMSP brightness fields.

2. Past and Present Land Cover

The distribution of past and present land cover was digitally compiled, at 1° resolution, from approximately 100 published sources, complemented by a large collection of satellite data, by Matthews [14]. Past land cover reflects natural vegetation prior to agricultural modifications; present land cover includes farmland. Of the 155 cells in our study zone, forest originally covered 82 cells east of the Mississippi River (Table 1). The region from 90–95°W was covered by deciduous forest and tall grass prairie interspersed with 10–40% woods. West of 95°W, grass became progressively shorter and trees and shrubs scarse. In general, these conditions lasted to the east of the Appalachian Mountains until the 18th century. West of the mountains, the influence of settlers was first felt in the 19th century, when deforestation in the east reached its peak and when spells of unfavorable weather affected farmland in New England [15, 16]. Since then, partial reforestation has taken place east of the Appalachians [17, 18].

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Table 1. *Past and Present Surface Albedo under Deep Snow Cover in the 155 One by One Degree Cells Between 71–105° W and 38–43° N from the ANTHRO1 and ANTHRO2 Models.* The present albedo in both models is the average of all cells which in the past were occupied by the given natural ecosystem. Mean albedos of the cultivated ecosystems used in ANTHRO1 and the number of cells throughout the Northern Hemisphere from which the albedo of each ecosystem in the ANTHRO1 model was determined (# cells NH) are also given

Ecosystem	# cells Past	ANTHRO1 # cells NH	ANTHRO1 Albedo Past	ANTHRO1 Present	ANTHRO1 Difference	ANTHRO2 Albedo Past	ANTHRO2 Present	ANTHRO2 Difference
Natural:								
Deciduous forest with evergreens	18	510	.47	.54	+.07	.24	.45	+.21
Deciduous forest without evergreens	64	504	.43	.57	+.14	.28	.57	+.29
Tall/medium/short grassland with 10–40% woody cover	24	153	.62	.67	+.05	.54	.70	+.16
Tall/medium/short grassland with shrub cover	1	371	.73	.68	−.05	.64	.78	+.14
Tall grassland, no woody cover	13	0	(.68)est	.68	0	.64	.75	+.11
Medium grassland, no woody cover	20	25	.70	.69	−.01	.70	.76	+.06
Short grassland, meadow no woody cover	14	382	.70	.69	−.01	.76	.73	−.03
Zonal totals and averages	155		.55	.62	+.07	.45	.64	+.19
Cultivated:								
75% cultivated, 25% deciduous with evergreen		294	.57					
75% cultivated, 25% deciduous without evergreen		187	.58					
75% cultivated, 25% grassland with woody cover		92	.61					
75% cultivated, 25% grassland		3	.72					
100% cultivated		295	.68					
		2816						

At present, only 17 forested cells in the eastern half of the study zone and 13 grassland cells in the western half are dominated by natural vegetation. All other cells are at least 75% cultivated. West of the Mississippi, large farms prevail and most cells are classified as 100% cultivated, while to the east small farming operations result in most cells being classified as 75% cultivated and 25% natural vegetation.

3. ANTHRO1 Model

The first model (ANTHRO1) assumes that each ecosystem had the same average albedo in the past as at present. Winter albedos of the six ecosystems in the study area were derived by averaging DMSP measurements in over 2800 $1° \times 1°$ lat/long cells from throughout the Northern Hemisphere. The surface albedo of individual cells was obtained by analyzing selected DMSP transparencies from 1978 and 1979 on an image processor [19]. The spectral range of the DMSP sensor is 0.4 to 1.1 μm. Scene brightness of each $1° \times 1°$ cell was converted to surface albedo by linear interpolation between standard bright and dark snow-covered surface elements with known albedo. Brightness was measured if, in a set of multi-temporal imagery, the presence of deep (over 15 cm) and fresh snow cover was indicated. Cell albedo so calculated may be up to 0.10 too low or 0.05 too high, with the errors randomly distributed [19].

The average albedo of past and present naturally-vegetated ecosystems found in the U.S. study zone ranges from 0.43 over deciduous forest to 0.73 over grassland with shrub cover (Table 1). The average albedo of fully-cultivated land under snow is 0.68. Partly-cultivated ecosystems, with 75% of the area under plow, have albedos which range from 0.57 over former deciduous forest to 0.72 over former grassland. The past areally-weighted albedo of the study zone under deep snow in the ANTHRO1 model is 0.55, compared to 0.62 today. Cultivated cells range from 0.05 lower to 0.25 higher than when naturally vegetated.

While the ANTHRO1 model may give reasonable results when analyzing anthropogenic albedo change on a hemispheric scale, there are apparent difficulties in applying it to a regional level. The assumption that a particular ecosystem had the same albedo in the past and at present is a major source of error. This is particularly evident over deciduous forests, which today are composed mostly of secondary growth with lower and thinner canopies, and therefore higher albedo under snow than primary forests. In addition, few if any cells in the study zone are fully covered by woodland at present. They are interspersed with meadows, fields and other man-made openings. Therefore, the ANTHRO1 model underestimates the human-induced albedo change over areas where forests existed in the past.

Another problem of the ANTHRO1 approach is the apparent decrease of surface albedo over former grasslands which are now cultivated. This misleading result is due to the very high winter albedo of central U.S. farmland, which is considerably higher than the hemispheric average of a fully cultivated ecosystem used as model input.

4. ANTHRO2 Model

The second model (ANTHRO2) employs measurements gathered within the study region. The present-day albedo distribution is taken directly from the DMSP data set [19]. The albedo of snow-covered 1° cells ranges from 0.35 over a forested cell in New England to 0.78 in several cells composed of fields and pasture in Nebraska and Kansas. The areally-weighted albedo of the study zone under deep snow is 0.64. Values are generally higher than 0.70 west of the Mississippi River, and decrease below 0.50 over the Appalachian Mountains and farther east.

ANTHRO2 albedos representative of past natural vegetation are derived from aerial measurements of broadband (.28–2.80 μm) hemispheric surface albedo of relatively undisturbed sites in New York and New Jersey [20]. Data were collected from an instrumented aircraft on flights at an average altitude of 200 m and documented by fisheye photographs. Approximately 90% of the reflected signal came from an area of 0.50 km^2. The confidence limit of gathered data is ±4% of the albedo value. For ANTHRO2 input, albedos of fully snow-covered targets are averaged from measurements taken around noon on February 14 and 18, 1983. The ground was covered with 30–60 cm deep 2 day old dry snow on the 14th and with 20–40 cm deep 6 day old wet snow on the 18th. The sky had an altostratus overcast during the first flight and was clear during the second one. The average albedo of uninterrupted snow surfaces on these two days, as measured at ground test sites, was 0.83 and 0.75, respectively. Aircraft derived values range from 0.24 over a deciduous forest with 25% evergreens to 0.76 over short grassland (Table 1). Values of other ecosystems varied as a function of the height and density of vegetation. These ecosystem albedos are applied in ANTHRO2 to the past land-cover distributions of Matthews [14], described in the previous section.

According to the ANTHRO2 model, the past areally-weighted albedo of the study zone under deep snow was 0.45, which is 0.19 lower than today (Fig. 1, Table 1). The present albedo of snow-covered previously-forested cells is approximately twice as large as for past undisturbed conditions, with the difference ranging from + 0.09 to + 0.48. The lowest difference comes from a cell classified as naturally vegetated today. In ANTHRO2, the average albedo of the present quasi-natural forested cells is 0.17 to 0.20

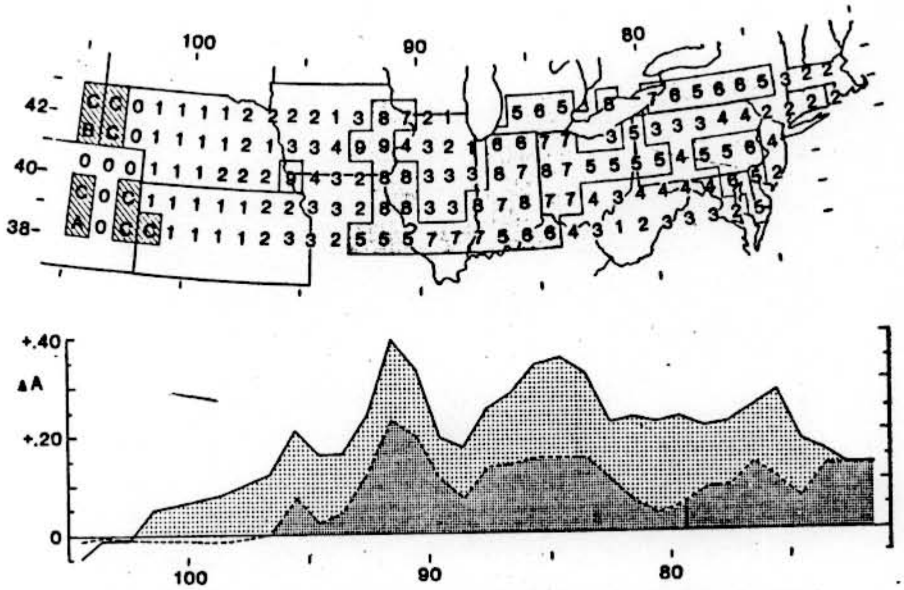

Fig. 1. (top) Change of surface albedo of fully snow-covered land in the central and eastern U.S. between the past natural vegetation and the present conditions. From the ANTHRO2 model, in 0.05 increments. Recent decrease by $A = -0.15$ to -0.11, $B = -0.10$ to -0.06 and $C = -0.05$ to -0.01. Increase of albedo by $0 = 0$ to $+0.04 \ldots 9 = +0.45$ to $+0.49$. (bottom) The average albedo change across the 38–43°N zone derived from the ANTHRO1 (dashed line) and ANTHRO 2 (solid line) models

higher than that in the past, due to the presence of secondary growth and numerous man-made openings today.

Albedo over areas of former medium and tall grasslands is from 0.05 to 0.14 higher today than in the past. It is up to 0.24 higher where, in the past, tall grasslands were interspersed with woods. Albedos today are lower in the extreme west of the study zone. This is due to the presence of towns, roads, windbreaks etc. in the area of former short grasslands.

The forests measured for the ANTHRO2 calibration of past (primary) forest ecosystems are secondary growth and are less dense than the primary ones. Thus, our estimate of past albedo may be too high. However, this potential error is at least partly compensated for by natural openings, including snow-covered frozen lakes, forest blowdowns, etc., which to some degree exist in almost any 1°×1° cell, but are not taken into account in the ANTHRO2 model. We therefore believe that the difference between the past and present albedo computed from the ANTHRO2 model is on the average realistic and more accurate than that of ANTHRO1. Only between 90–93°W, where the natural forest was probably not as dense as the present vegetation used in the ANTHRO2 calibration [21], may the lower ANTHRO1 values be closer to reality.

5. Conclusions

Overall, the results of the ANTHRO2 model of anthropogenic winter albedo change in the study zone are considered closer to reality than those of ANTHRO1. More information is needed on the past density of forests across the study zone and on representative albedo values over natural vegetation and cultivated land before more definitive results can be obtained.
The approximate doubling of surface albedo in snow covered deforested portions of the U.S. and increases of up to about 0.20 over former medium and tall grasslands (Fig. 1) may be considered representative of albedo changes in other populated middle latitude regions where significant deforestation has also occurred, such as in Europe and portions of east Asia [22, 23]. In these zones, the winter surface albedo and, in turn, boundary-layer climates have become considerably more sensitive to the presence and duration of snow cover. However, whether the conversion of middle latitude woodlands and grasslands to farmland resulted in a measurable change in regional weather patterns is uncertain, since adequate observational records are not available.

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