

Radiative forcing due to anthropogenic vegetation change based on MODIS surface albedo data

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Received 6 July 2005; revised 21 September 2005; accepted 26 September 2005; published 9 November 2005.

[1] In this study we use the capabilities of the MODerate Resolution Imaging Spectroradiometer (MODIS) land surface product to estimate the radiative forcing due to surface albedo changes caused by anthropogenic vegetation changes. We improve the representation of the present surface albedo by using data retrieved from MODIS. The change in surface albedo is based on the current vegetation land cover from MODIS, the MODIS surface albedos for those vegetation types, and a data set for potential natural vegetation. We arrive at a radiative forcing due to anthropogenic vegetation changes of -0.09 Wm^{-2} since pre-agriculture times to present, weaker than most earlier published results for this climate forcing mechanism. This is mainly due to a lower surface albedo associated with cropland and further with the use of MODIS data to allow us to constrain the surface albedo change. **Citation:** Myhre, G., M. M. Kvalevåg, and C. B. Schaaf (2005), Radiative forcing due to anthropogenic vegetation change based on MODIS surface albedo data, *Geophys. Res. Lett.*, 32, L21410, doi:10.1029/2005GL024004.

1. Introduction

[2] Radiative forcing of surface albedo changes caused by anthropogenic land use changes is quite uncertain but given a best estimate since pre-industrial time of -0.2 Wm^{-2} in [Houghton *et al.*, 2001], with a range from 0 to -0.4 Wm^{-2} . The land use changes that are taken into account are mainly for agricultural activity with deforestation as the major cause. An essential role for the magnitude of the forcing is the much higher albedo for snow-covered non-forested regions than for forested areas [Betts, 2000, 2001; Hansen *et al.*, 1998]. Myhre and Myhre [2003] found in a sensitivity study a somewhat larger range of likely radiative forcing from this mechanism than in Houghton *et al.* [2001], and a positive forcing was not ruled out although not very probable. Several vegetation data sets and surface albedo sets for vegetation types was investigated in the sensitivity study. Importantly, the main cause for the relatively large range in the radiative forcing was owing to the surface albedo of cropland. The significance of the cropland surface albedo was illustrated by using 3 values (0.15, 0.18, and 0.20) based on published results [Myhre and Myhre, 2003]. In the experiment where

only the cropland surface albedo was changed the resulting radiative forcing was -0.06 , -0.20 , and -0.29 Wm^{-2} , respectively. Similar results are given by Matthews *et al.* [2003] where simulations were performed for cropland surface albedo of 0.17 to 0.20 with corresponding radiative forcing of -0.15 and -0.28 Wm^{-2} , respectively.

[3] Earlier studies of radiative forcing due to albedo changes are based on vegetation data and the associated surface albedo data for each of the vegetation types (which are treated as constants). Some recent studies have analyzed the remote sensed MODIS data and have found surface albedo values for the various vegetation types [Gao *et al.*, 2005; Jin *et al.*, 2002; Zhou *et al.*, 2003]. It is noteworthy that these studies all indicate a rather low growing season surface albedo for cropland. Two of these studies [Gao *et al.*, 2005; Jin *et al.*, 2002] also include investigations of the impact of snow cover on the annual surface albedo. These reveal the complicated role snow covers plays on surface albedo change as it not only differs for various vegetation types but also on a wide range of factors such as snow depth, time since last snow fall, and history of temperature and wind since last snow fall [Aoki *et al.*, 2003].

[4] Here we use the MODIS satellite product for the current surface albedo [Schaaf *et al.*, 2002] and combine that with the MODIS vegetation data along with surface albedo with regional variation for the estimation of the pre-agriculture albedo. With this approach the current surface albedo is much better characterized than in earlier studies and this allows us to constrain the change in surface albedo from the anthropogenic vegetation changes. We then perform radiative transfer calculation to estimate radiative forcing based on these surface albedo changes.

2. The MODIS Surface Albedo and Vegetation Product

[5] For the present surface albedo the MODIS product (MOD43C1) of white-sky (completely diffuse) and black-sky (direct beam) is adopted [Gao *et al.*, 2005; Lucht *et al.*, 2000; Schaaf *et al.*, 2002]. The surface albedo has been validated to stage one with the highest quality retrievals generally comparing to field measurements within 0.02 [Jin *et al.*, 2003]. The MODIS product is produced every 16 days and represents the best estimate of albedo that can be achieved for that 16 day period. In this study we focused on the four specific months and used the mean over four years (2001–2004) of the 16-day albedo data for each of these months. The four months (February, May, August, and November) were selected to represent the four seasons. The white-sky and black-sky albedos were combined to an actual surface albedo and here information from meteorological data and the radiative transfer model (see

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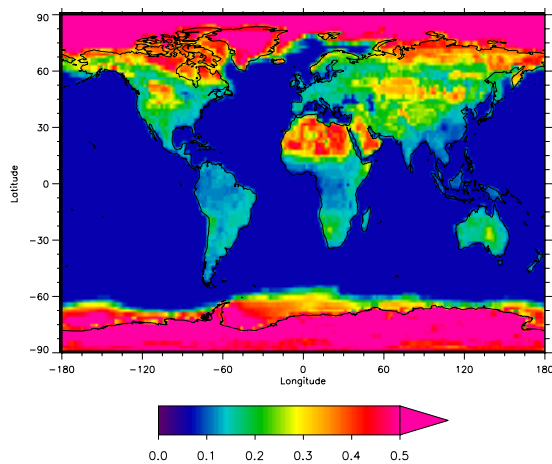


Figure 1. Modeled annual mean surface albedo based on the MODIS black-sky and white-sky surface albedo.

below) are used to generate realistic modeled fields of mean annual surface albedo as shown in Figure 1. Over ocean and in the polar night predefined values have been set. Figure 1 clearly shows the high surface albedo over deserts but illuminates the differences in surface albedo that exist in arid regions. A minimum in the surface albedo is in tropical regions. At northern mid latitudes relatively high annual surface albedos are found due to snow cover during the winter season.

[6] To establish the change in surface albedo due to vegetation changes, three IGBP classes of anthropogenic activity has been considered (cropland, urban, and cropland mosaic). Only in regions where the MODIS vegetation data [Friedl *et al.*, 2002] shows that these three classes currently exist has a surface albedo change been performed. The MODIS vegetation product has fractional data on a 0.25 degree resolution for 18 vegetation classes (see Table 1). The stated accuracy of the MODIS land cover product (<http://geography.bu.edu/landcover/userguide/c/consistent.htm>) is 75–80% globally supported by classifi-

cation of unseen training sites and of the confidence values included in the product. In addition, the MODIS vegetation data have been compared to the Global Land Cover 2000 data set and shown to compare well for forest, urban, cropland, grassland, and barren whereas the two data sets did not compare so well for shrubland/savannas and wetlands [Giri *et al.*, 2005]. In areas with anthropogenic influence on the vegetation cover (the three above mentioned classes) the vegetation cover has been replaced by the potential natural vegetation cover given by [Ramankutty and Foley, 1998]. To calculate the difference in the surface albedo (based on current MODIS vegetation data of anthropogenic vegetation and potential natural vegetation) we exploit the availability of both surface albedo and vegetation cover products from MODIS. Seasonal and regional (if necessary) information has been established in regions having more than 95% of a single vegetation type. Note that we determine snow free MODIS values and then model the snow impact on the surface albedo (see below). The result of the investigation for the snow free black-sky albedo is shown in Table 1. Similar analysis for the white-sky albedo shows generally 10% higher values compared to the black-sky albedo. Importantly the surface albedo for snow free cropland is relatively low (0.14–0.17) in accordance with other studies analyzing the MODIS data [Gao *et al.*, 2005; Jin *et al.*, 2002; Zhou *et al.*, 2003]. Some regional and seasonal variations in the surface albedo for the anthropogenic influenced vegetation types can be seen although not major differences (less than 20%). However, for some of the other vegetation types important regional differences have been implemented. The seasonal (and sometimes regional) varying black-sky surface albedo (Table 1) and white-sky surface albedo are essential for the calculation of change in the surface albedo.

[7] The pre-agriculture surface albedo is calculated as the difference between the current surface albedo retrieved from MODIS and the anthropogenic change in surface albedo. Our approach is an improvement compared to earlier studies by the use of the retrieved current surface albedo. Still there is a significant uncertainty in the calculation of the change

Table 1. Black-Sky Snow Free Surface Albedo Values for Various Land Cover Types According to the IGBP Vegetation Classes Given for 4 Months as 4 Years Mean^a

Vegetation Type	February	May	August	November
Evergreen needleleaf (1)	0.096	0.090	0.096	0.092
Evergreen broadleaf in Amazonas (2)	0.122	0.119	0.124	0.127
Evergreen broadleaf excluding Amazonas (2)	0.121	0.116	0.118	0.127
Deciduous needleleaf (3)	0.103	0.095	0.110	0.103
Deciduous broadleaf (4)	0.116	0.137	0.140	0.119
Mixed forest(5)	0.096	0.101	0.119	0.100
Open shrubland 35S–45N (7)	0.220	0.219	0.209	0.217
Open shrubland Australia (7)	0.177	0.177	0.177	0.173
Open shrubland other (7)	0.137	0.126	0.141	0.129
Woody savanna (8)	0.106	0.117	0.110	0.112
Savanna (9)	0.140	0.141	0.142	0.133
Grassland (10)	0.185	0.165	0.165	0.178
Cropland Eurasia (12)	0.144	0.140	0.150	0.139
Cropland East Asia, India (12)	0.162	0.161	0.151	0.156
Cropland other (12)	0.162	0.151	0.165	0.159
Barren in Sahara and the Arabian desert (16)	0.365	0.356	0.353	0.365
Barren in Asia (16)	0.222	0.229	0.232	0.228
Barren excluding Sahara, the Arabian desert and Asia (16)	0.208	0.215	0.175	0.215

^aData in the analysis are based on high quality and snow free quality assurance flag.

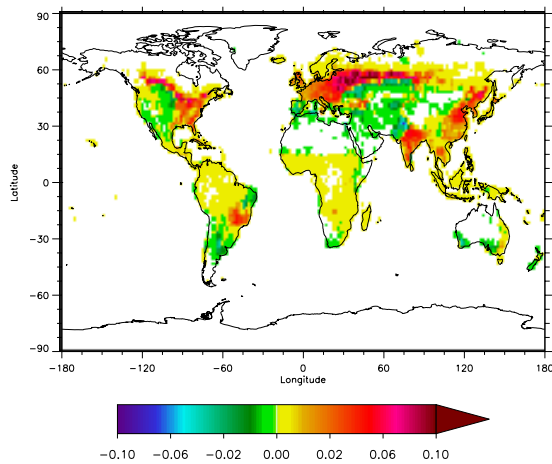


Figure 2. Annual mean surface albedo change caused by anthropogenic vegetation changes. Note the non linear scale.

in the surface albedo, which is mainly with respect to the influence of snow. Therefore, we allow an important constrain on the change in surface albedo such that the pre-agriculture can not be lower than 0.081 in anthropogenic affected vegetation areas. This lower bound is based on minimum surface albedo values found in [Gao *et al.*, 2005]. Note that the importance and justification of this lower bound is due to the use of the current surface albedo retrieved from MODIS and thereafter the human influenced (mainly deforestation) change in the surface albedo is subtracted. Without this constraint in the pre-agriculture surface albedo unrealistic low values may occur.

3. Radiative Transfer Model

[8] An atmospheric radiative transfer code using the discrete ordinate method [Myhre and Myhre, 2003; Stamnes *et al.*, 1988] is adopted for the radiative forcing calculations. The model includes absorption by atmospheric gases, Rayleigh scattering, scattering by clouds, and absorption and scattering by aerosols.

[9] The meteorological data used in the radiative transfer calculations are from the European Centre for Medium-range Weather Forecasts (ECMWF). Monthly mean data for water vapour, clouds, snow depth, and snow cover are used. Treatment of the surface albedo when snow is present has been made as in the work by Myhre and Myhre [2003] with varying albedo between the snow free albedo and a maximum snow cover surface albedo depending on the snow depth, which is then given for each land cover type. The maximum surface albedos for each of the snow covered vegetations are also taken from Gao *et al.* [2005]. Data for 5 aerosol types (sea salt, mineral dust, sulfate, black carbon, and organic carbon) as monthly mean are based on simulation from a chemistry transport model involved in a global aerosol intercomparison study (<http://nansen.ipsl.jussieu.fr/AEROCOM>). The meteorological data represent the year 1996 and simulations are performed on a T63 resolution (about 1.9×1.9 degrees).

[10] The surface albedo, α , is calculated from an interpolation of the black-sky and white-sky albedo with the formula [Schaaf *et al.*, 2002]

$$\alpha = (1 - S)\alpha_{bs} + S\alpha_{ws} \quad (1)$$

where α_{bs} is the black-sky albedo, α_{ws} is the white-sky albedo, and S is the fraction of diffuse sunlight reaching the surface. All these variables have important geographical variations. The geographical distributions of diffuse and direct sunlight have been calculated with the radiative transfer code for each month. In the calculation of S it is important that scattering and absorbing media in the atmosphere to be well represented.

4. Results

[11] Figure 2 shows the calculated change in surface albedo caused by the vegetation changes. The usual increase in the surface albedo at mid-latitudes in the northern hemisphere can easily be seen. This is a result of deforestation for agricultural activity. The increase of the annual mean surface albedo is more than 0.1 in certain areas and is larger over Europe than in the North-America. In some areas the conversion of grassland to cropland has reduced the surface albedo, but the effect is of smaller magnitude than in regions with deforestation. In northwestern part of India and Pakistan a decrease of the surface albedo is simulated, but this is due to the potential natural vegetation data indicate shrubland and even some small barren areas in this region. In all cases with a decrease of the surface albedo, the simulated pre-agricultural surface albedo is not unrealistically high. The impact of constraining the surface albedo change (not allow the pre-agricultural surface albedo to be below 0.081) is to reduce the change substantially over Europe. This is especially over the eastern part of Europe where the albedo change is reduced by around 30%. In other regions the impact of constraining the surface albedo is of much less importance.

[12] The radiative forcing for the simulated change in surface albedo is shown in Figure 3. The pattern in the

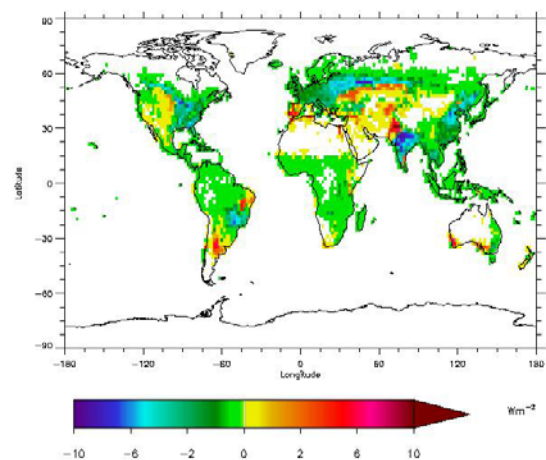


Figure 3. Annual mean radiative forcing due to surface albedo changes caused by anthropogenic vegetation changes. Note the non linear scale.

radiative forcing is similar to the pattern of the change in the albedo, but modification for an equal change in the surface albedo results in a larger radiative forcing in tropical areas compared to at mid and high latitudes [Myhre and Myhre, 2003]. Radiative forcing is with a few exceptions within a magnitude of 10 Wm^{-2} . Compared to earlier studies the pattern of the radiative forcing is rather similar [Betts, 2001; Hansen et al., 1998; Myhre and Myhre, 2003]. The global and annual mean radiative forcing is calculated to be -0.09 Wm^{-2} , within the range given in [Houghton et al., 2001] but significantly weaker than the best estimate. Without constraining the surface albedo change we arrive at a radiative forcing of -0.14 Wm^{-2} which is still weaker than most earlier estimates.

[13] Aerosols (of natural and anthropogenic sources) reduce the incoming solar radiation by scattering and absorption. This weakens the radiative forcing due to surface albedo by about 10%. However, it also alters the fraction of diffuse radiation that is of importance for the distribution of white-sky and black-sky albedo. This effect strengthens the radiative forcing due to surface albedo change but is a small effect compared to the shielding effect of solar radiation by the aerosols.

5. Summary

[14] The main finding from this study is that radiative forcing from surface albedo changes caused by anthropogenic vegetation changes is generally weaker than found in earlier studies. This is mainly due to the lower surface albedo associated with cropland but also in that we constrain the surface albedo change by using the present surface albedo from MODIS as limits on the pre-agricultural surface albedo. The first of these results in a radiative forcing of -0.14 Wm^{-2} over the period from pre-agriculture to present whereas in the latter as we see as our best estimate results in a radiative forcing of -0.09 Wm^{-2} . The importance of constraining the surface albedo change is due to limited knowledge about the influence of snow cover. The global mean radiative forcing due to anthropogenic vegetation changes is found to be relatively weak in this study. However, the regional radiative forcing is strong in certain regions and may have given regional climate changes. Note also that our study in accordance with [Gao et al., 2005; Jin et al., 2002; Zhou et al., 2003] find lower surface albedo for cropland than for grassland. It is thus important in climate models to use different surface albedo for these two land cover types in modeling of surface albedo changes and associated climate changes.

[15] Note that our radiative forcing estimate is since pre-agricultural time whereas since pre-industrial time as given in [Houghton et al., 2001]. Typically around one-quarter to one-third of the radiative forcing due to surface albedo

changes caused by vegetation changes have occurred before the beginning of the industrialization [Betts and Fallon, 2005; Myhre and Myhre, 2003].

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