# Land boundary conditions from MODIS data and consequences for the albedo of a climate model

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[1] This paper compares seasonal and spatial variations of MODIS albedos with those from the Community Land Model (CLM2). MODIS surface albedo data from September 2000 to August 2002 were used to investigate the model biases. To assess how inaccuracies in the land surface data used in CLM2 contribute to the model albedo biases, we created a new land surface dataset using the highest quality reprocessed MODIS products of leaf area index (LAI), plant functional type (PFT), and fraction of bare soil. A sensitivity experiment using this new data set quantifies the role of each variable and its contribution to the albedo biases. Our results indicate that most of the positive albedo biases result from an underestimation of LAI or an overestimation of the grass/crop fraction. Such biases can be largely reduced when the new data set is used. These results provide information on improving albedo in the model. This new land surface data set is available for use in CLM2. *INDEX TERMS:* 1640 Global Change: Remote sensing; 3307 Meteorology and Atmospheric Dynamics: Boundary layer processes; 3322 Meteorology and Atmospheric Dynamics: Land/atmosphere interactions. **Citation:** Tian, Y., R. E. Dickinson, L. Zhou, R. B. Myneni, M. Friedl, C. B. Schaaf, M. Carroll, and F. Gao (2004), Land boundary conditions from MODIS data and consequences for the albedo of a climate model, *Geophys. Res. Lett.*, *31*, L05504, doi:10.1029/2003GL019104.

## 1. Introduction

[2] Albedo has been used as a key parameter in climate models to characterize the land surface processes [*Dickinson et al.*, 1993]. It determines how much solar radiation is absorbed by the surface and thus the surface energy balance. Hence a more realistic representation of albedo in climate models will significantly improve the accuracy of climate simulation and prediction.

[3] Most climate models represent the land surface albedo by two-stream approximations for vegetation and by a limited number of prescribed values for bare soils [*Dickinson et al.*, 1993]. Notable albedo differences have been identified in the latest developed Community Land Model (CLM2) [*Bonan et al.*, 2002a] and its earlier versions in comparison with satellite observations [*Oleson et al.*, 2003; *Zhou et al.*, 2003; *Wang et al.*, 2004]. These studies found significant biases in Sahara and the Arabian Peninsula and over snow-covered northern middle and high latitudes and a relatively small bias over most snow-free vegetated regions. Such biases were attributed to inaccurate specification of land surface parameters such as leaf area index (LAI), stem area index (SAI), leaf optical properties, and soil albedo combined with inadequate treatments of snow or soil underlying vegetation.

[4] Could the albedo biases in CLM2 be reduced using a more accurate and consistent land surface dataset? Most of the land surface datasets currently used in climate models were derived from AVHRRs, whose quality may be degraded by atmospheric effects, satellite drift and change-over [*Gutman*, 1999]. Another important variable that determines albedo in climate models is fractional vegetation cover (FVC), whose accuracy is generally not assessed due to lack of data. Since FVC indicates the horizontal heterogeneity of vegetation, errors in its specification could result in large albedo biases in climate models even though the LAI were specified precisely. In addition, sensitivity experiments should be conducted to quantify the role of variables that are suspected to be responsible for the albedo biases.

[5] The recent availability of multiple high quality MODIS land data makes it possible to investigate such questions. This paper compares CLM2 parameters with those from MODIS to investigate possible reasons for albedo biases in CLM2. For this purpose, we consider the seasonally and spatially varying albedos, LAI, plant functional type (PFT), snow fraction, and fraction of bare soil. We first develop a new land surface data set for use in CLM2 from MODIS data and then examine its improvements on CLM2 albedo. Our results provide useful information about how to improve albedo parameterizations in the model.

## 2. Data and Methods

### 2.1. MODIS and Model Albedo

[6] We use two years of the MODIS broadband albedo data (Collection 4) for visible (VIS, 0.4–0.7 μm) and near-infrared (NIR, 0.7–5.0 μm) from September 2000 to August 2002 at 0.05° resolution. The MODIS albedo was generated by a semiempirical, kernel driven linear bidirectional reflectance distribution function model [*Schaaf et al.*, 2002]. This model relies on the weighted sum of three parameters retrieved from the multidate multiangular cloud-free atmospherically corrected surface reflectances at 1-km resolution, acquired by MODIS in a 16-day period. The MODIS albedos represent the best quality retrieval possible over each 16-day period and consist of local noon black-sky (direct) and white-sky (wholly diffuse) albedos. Since the

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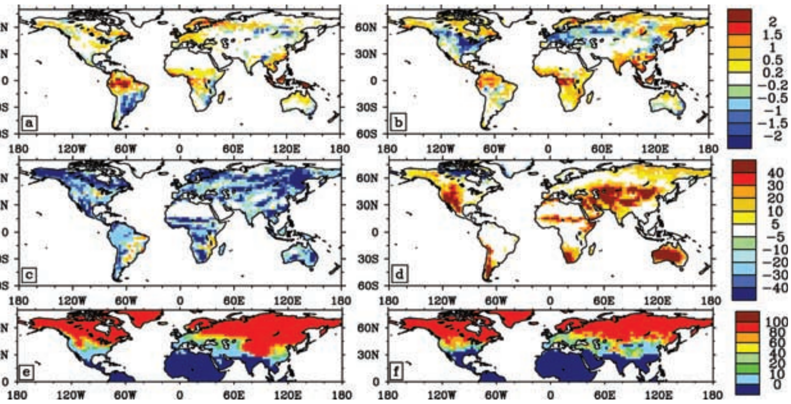


**Figure 1.** Spatial pattern of (a) LAI difference (new-old) in Feburary, (b) as (a) but for July, (c) differences in grass/crop fraction (new-old), (d) as (c) but for bare soil fraction, (e) snow fraction in CLM2 in Feburary, and (f) as (e) but from MODIS.

white-sky albedos vary spatially as do the black-sky albedos, only results of the former are shown in this paper.

[7] Model VIS and NIR albedos were produced from the latest version of CLM2 (version 2.02) coupled to the Community Atmosphere Model, using observed sea surface temperature from 1979 to 1989. CLM2 is the land surface parameterization used with the Community Climate System Model at about $2.8^\circ \times 2.8^\circ$ resolution [*Blackmon et al.*, 2001]. Each model grid cell is divided into four primary land cover types: glacier, lake, wetland, and vegetation. The vegetated portion of a grid cell is further divided into patches of up to 4 of the model's 15 PFTs, each with its own leaf and stem area index and leaf optical properties. Albedo at each grid is calculated as a sum of albedos for each land cover types based on their fractions. Details about the model albedo can be found from *Oleson et al.* [2003]. Here we only use the model diffuse albedos (comparable to the MODIS white-sky albedos).

[8] A climatology of monthly albedo was produced for both the model and MODIS. The model albedos are from the last 10 years data of the 11-year simulations. The MODIS albedos were first aggregated spatially to the model grids using area weighting and then temporally to monthly data.

### 2.2. A New Land Surface Date Set

[9] To assess the accuracy of the land surface dataset currently used in CLM2 (referred as the old data thereafter), we create a new land surface dataset from the latest MODIS land products using similar procedures as described by *Bonan et al.* [2002b].

[10] We aggregate MODIS 500m collection 3 Global Vegetation Continuous Fields (VCF) [*DeFries et al.*, 1999] from 2000–2001 to generate 1 km FVC data. The VCF data contain percent of tree cover (tall trees), herbaceous cover (shrubs and grasses) and bare. The sum of these three components equals 100% ground cover. The FVC data is calculated as a sum of percentage of tree cover and herbaceous cover.

[11] We generate a 15 PFT dataset at $0.5^\circ \times 0.5^\circ$ resolution from the MODIS 1 km PFT and IGBP land cover maps. The MODIS PFT map consists of 7 primary PFTs, needleleaf evergreen or deciduous tree, broadleaf evergreen or deciduous tree, shrub, grass and crop. It is expanded to 15 PFTs based on climate rules [*Bonan et al.*, 2002b]. Since the current VCF data does not distinguish between evergreen versus deciduous and broadleaf versus needleleaf for the tree cover or shrub versus grass for the herbaceous cover, we assume that each 1 km pixel has only one PFT and its abundance equals its FVC. The bare fraction is 1-FVC. The old PFT data was derived without access to consistent FVC data and so assumed the non-tree-covered land in forests, savanna, and grasslands was covered by grasses, in shrub lands by shrubs, in croplands by crops. The new PFT data define a pixel as grass, shrub or crop only if it is classified so by the PFT map and its fraction as FVC. This is a major difference between the old and new PFT data. The 1-km data are aggregated to grid cells at $0.5^\circ$ resolution by averaging the 1-km percentages per $0.5^\circ$ grid cell, which normalized the percent of each grid cell covered by a particular PFT by the vegetated area [*Bonan et al.*, 2002b]. The bare ground in each grid cell is always considered to be the cumulative canopy opening.

[12] We generate an LAI dataset at $0.5^\circ$ resolution from two and half years of collection 4 MODIS 1-km LAI data [*Myneni et al.*, 2002] in 2000, 2001, and January through June in 2003, with 8-day compositing periods. These data are further composited over 4 (or 3) consecutive 8-day periods to produce monthly data. To minimize cloud and snow contamination, the 2.5-year data with the best quality are further composited to produce a climatology of monthly LAI. These data are used to derive the seasonal course of LAI for every PFT at a $0.5^\circ$ grid cell. First, LAI at 1-km is divided by the FVC to produce LAI with respect to vegetated area only. Second, evergreen needleleaf PFTs are adjusted to be no less than 70% of their maximum LAI to correct the MODIS biases of lower winter LAI values in the presence of snow [*Tian et al.*, 2004]. It is no longer necessary to adjust the evergreen broadleaf LAI since the current MODIS data has substantially improved LAI retrievals in tropical and subtropical regions compared to AVHRR. Third, for each PFT, a pure PFT LAI is estimated at a $0.5^\circ$ grid cell by averaging only the LAIs over 1-km pixels whose abundance of the PFT is greater than 60%. The old model LAI was derived from only one year of AVHRR data (April 1992 to March 1993) based on NDVI-LAI relationship [*Bonan et al.*, 2002b]. Thus, improvements with the present analysis should be expected.

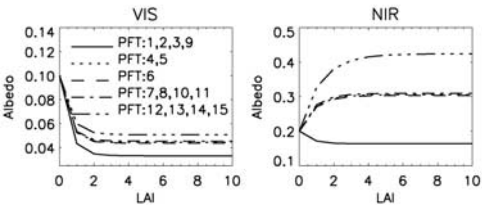


**Figure 2.** Canopy local noon diffuse albedo as a function of leaf area index simulated from the two-stream scheme for the 5 types of leaf optical properties used to represent all 15 PFTs in CLM2 [*Bonan et al.*, 2002a]. PFTs 12 ~ 15 represent grass/crop. The canopy underlying soil albedo is set as 0.1 for VIS and 0.2 for NIR.

[13] Finally, for use in CLM2, the 0.5° data are aggregated into the model grids. The surface data for land cover types of water, wetland, lake, and snow-ice are unchanged and not considered here. We also use the MODIS Collection 4 snow product to examine differences in snow cover between the model and MODIS.

## 3. Results and Discussion

[14] Two model simulations are performed to test albedo changes due to differences in the land surface data. For simplicity, the model albedo using the old data is referred as "the control run" and that using the new data as "the experiment". Comparison of the control to MODIS albedo locates the major albedo biases as by *Oleson et al.* [2003] while comparison between the experiment and control run albedo is used to demonstrate the major improvements after the new data are used.

### 3.1. Differences in the Land Surface Data

[15] Figure 1 shows the differences in Feburary and July LAI, fraction of grass/crop, and fraction of bare soil between the new and old data. It also shows the differences between the snow fraction determined by the model and that detected by MODIS. The new LAI is larger than that of the old data over the Amazon, central Africa, southeastern Asia, and north Europe by at least 1.5, and by about 0.5–1.0 over most areas beyond 60°N in both Feburary and July. The new values are smaller by about 0.5–1.5 over extra-tropical South America in February and over southeastern USA and most Eurasian areas (30°–60°) in July.

[16] *Zhou et al.* [2003] indicate that canopy albedo is very sensitive to LAI for sparse vegetation with small LAI but becomes saturated for vegetation denser than LAI > 2.5. Furthermore, an increase in LAI will cause canopy albedo to decrease if the canopy is darker than its underlying surface. Otherwise, the opposite will be observed. Since snow has a much higher albedo than most other natural surfaces (e.g., 60–80% versus 10–30%), the albedo of a snow covered surface is particularly sensitive to LAI, especially in VIS. Such sensitivity to LAI should also be more evident in VIS in regions without snow since soil is commonly brighter than the canopy. Therefore, in regions where a positive LAI difference is observed in Figure 1, we expect to see a significant decrease in albedo over snow-covered areas (stronger in VIS than in NIR) or a less decrease over snow-free areas (mainly in VIS).

[17] The old data overestimate grass/crop fraction by about 20–40% globally, especially between 45°–70°N, except some areas over eastern South America and south-eastern Africa (Figure 1c). This exaggerated grass/crop cover results in overestimated model albedo due to the assumed large difference in optical properties between grass/crop and those for other vegetation types. Figure 2 shows the simulated canopy albedo in VIS and NIR as a function of LAI for the 5 types of leaf optical properties used to represent all 15 PFTs in the CLM2 [*Bonan et al.*, 2002a]. Grass/crop shows significantly higher albedo than

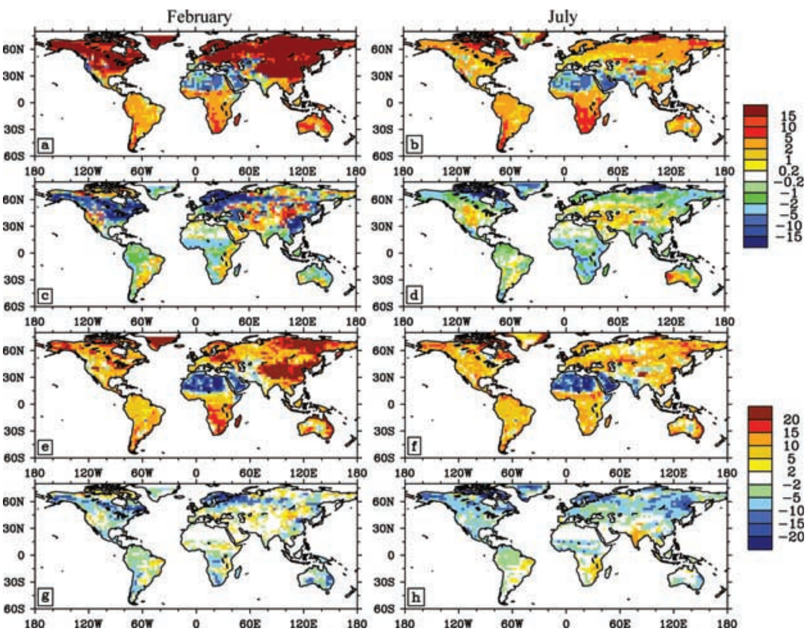


**Figure 3.** Spatial pattern of diffuse albedo differences for (a) control-MODIS VIS in Feburary, (b) control-MODIS VIS in July, (c) experiment-control VIS in Feburary, (d) experiment-control VIS in July, (e) control-MODIS NIR in Feburary, (f) control-MODIS NIR in July, (g) experiment-control NIR in Feburary, and (h) experiment-control NIR in July.

**Table 1.** Comparison of Grass/Crop Albedos Among CLM2 Simulations From the Two-Stream Scheme With LAI = 1, 2, and 4, Global Averages of 1km MODIS and AVHRR Summer Values, and Field Measurements [*Zhou et al.*, 2003; *Strugnell and Lucht*, 2001; *Bastable et al.*, 1993; *Hartmann*, 1994][a]

| | VIS | | NIR | | Broadband | | | |
|---|---|---|---|---|---|---|---|---|
| LAI | CLM2 | MODIS | CLM2 | MODIS | CLM2 | MODIS | AVHRR | Field Measurements |
| 1 | 0.0506 ~ 0.086 | 0.05 ~ 0.09 | 0.288 ~ 0.45 | 0.25 ~ 0.26 | 0.169 ~ 0.268 | 0.15 ~ 0.175 | 0.176 ~ 0.195 | 0.10 ~ 0.21 (mean 0.17 ~ 0.18) |
| 2 | 0.0508 ~ 0.057 | | 0.364 ~ 0.436 | | 0.207 ~ 0.242 | | | |
| 4 | 0.0508 ~ 0.051 | | 0.412 ~ 0.427 | | 0.231 ~ 0.239 | | | |

[a]The range of the CLM2 albedo is based on the variation of canopy underlying soil albedo between 0.05/0.10 and 0.24/0.48 for VIS/NIR.

other PFTs (more significant in NIR than VIS). The leaf single scattering albedo (leaf reflectance + transmittance) in VIS and NIR are only 0.15 and 0.7 for broadleaf forest but 0.18 and 0.83 for grass/crop in the model scheme. Therefore, in regions where a significant decrease in grass/crop is observed in Figure 1, we expect to see a corresponding decrease in albedo during snow-free seasons.

[18] The old data also underestimate bare soil fraction by about 10–30% over most sparsely vegetated areas such as the Sahel, Australia, west USA, and Tibet (Figure 1d). In general, an increase in soil fraction should increase the VIS albedo, especially over snow-covered regions as discussed before.

[19] Comparison of snow fraction between the model and MODIS indicates that the model has more snow near the southern boundary of the snow line over middle latitudes (Figures 1e and 1f) than is observed by MODIS. This discrepancy is even further exacerbated over regions with ephemeral snow since the MODIS albedo algorithm only uses the snowy pixel observations to make retrievals if the majority of days in a 16-day period have been snow covered. Therefore, large albedo differences are to be expected over regions where large snow fraction differences are present.

### 3.2. Albedo Improvements

[20] Figure 3 shows the global distribution of albedo biases in CLM2 (control-MODIS) and albedo improvements after the new data is used (experiment-control) in Feburary and July. Evidently, the CLM2 underestimates albedo over the desert and semidesert region, especially in the Sahara and the Arabian Peninsula where the bias could reach 0.2, and overestimates albedo over all other regions, especially in northern high latitude winter when snow is present. These results are generally consistent with those by *Oleson et al.* [2003] except for middle latitudes where they observed negative biases over some areas. Note that *Oleson et al.* [2003] use MODIS Collection 3 data and the CLM2 version 2.01 while we use the high quality MODIS Collection 4 data and the latest version of CLM2 (2.02), which contains major adjustments in the model's snow parameterizations and skin temperature scheme.

[21] When the new data are used, the model albedos are significantly improved. These improvements closely follow the differences in LAI and grass/crop fraction in spatial pattern and magnitude. Most of the significantly higher albedos over the snow-covered regions are largely reduced in winter over regions where LAI is underestimated. Over snow-free regions, the majority of the positive albedo biases in both NIR and VIS are reduced, mainly due to the reduction of grass/crop fraction and increase of LAI. The improvement is significant over the Amazon, Africa, Alaska, eastern Siberia, and northern Europe. The new data also decrease the summer negative biases in VIS in Arabian peninsulas and Asia (20°–45°N) mainly due to the increase of soil fraction.

[22] The albedo biases still remain over some regions however, possibly due to interactions of several factors. For regions with opposing effects (such as a decrease in grass/crop fraction and an increase in soil fraction), the changes in albedo could be very small and depend on which effect dominates. As no adjustment has been made to land surface data over Sahara, the albedo biases in this region are unchanged. The positive summer albedo biases over southeast of USA in VIS were enlarged because of the decrease of LAI. Large albedo biases are still expected for regions where snow fractions differ (such as over Eurasia). In addition, the assumption that each 1 km pixel has only one PFT is not accurate. A more realistic PFT dataset can be created when the percentage information about evergreen versus deciduous, broadleaf versus needleleaf for the tree cover and shrub versus grass for the herbaceous cover is available from MODIS products.

[23] In summary, the use of the new land surface data helps reduce the model albedo biases in the CLM2, especially over vegetated areas. These results highlight the importance of an improved specification of land surface parameters, especially LAI, PFT, FVC, and soil albedos. Furthermore, our analyses point out a possible problem of the CLM2 albedos associated with grass/crop, mainly in NIR. Albedo for this PFT from CLM2 is larger than that from MODIS, AVHRR, and field measurements (Table 1). Further analysis is needed to clarify whether an improved specification of the grass/crop optical properties will reduce the remaining biases. The new land surface dataset for use in CLM2 is available from: http://climate.eas.gatech.edu/ytian.

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