Research Article

Surface Albedo Assimilation and Its Impact on Surface Radiation Budget in Beijing

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Surface albedo is a crucial parameter in land surface radiation budget. As bias exists between the model simulated and observed surface albedo, data assimilation is an important method to improve the simulation results. Moreover, surface albedo is associated with the wavelength of the sunlight. So, solar radiation partitioning is important to parameterize the surface albedo. In this paper, the moderate resolution imaging spectroradiometer- (MODIS-) retrieved direct visible, direct near-infrared, diffuse visible, and diffuse near-infrared surface albedos were assimilated into the integrated urban land model (IUM). The solar radiation partitioning method was introduced to parameterize the surface albedo. Based on the albedo data from MODIS and the solar radiation partitioning method, the surface albedo data set for the Beijing municipal area was generated. Based on the surface albedo data set and the IUM, the impacts of the surface albedo on the surface radiation budget were discussed quantitatively. Surface albedo is inversely proportional to the net radiation. For urban areas, after assimilation, the annual average net radiation decreases about 5.6%. For cropland, grassland, and forest areas, after assimilation, the annual average net radiations increase about 20.2%, 24.3%, and 18.7%, respectively.

1. Introduction

Surface albedo is a crucial parameter in land surface radiation budget [1]. The parameterization of surface albedo is important in land-atmosphere interaction and coupling [1–8]. Surface albedo is not only associated with the soil moisture, soil color, and solar zenith angle [9–15] but also associated with the wavelength of the solar radiation [16, 17]. Although progress has been made in surface albedo simulation by land surface models, biases [10, 18] still exist inevitably between the simulation and observation.

Compared with the model simulation, surface albedo data retrieved from remote sensing images have their advantages [19–23] and are used and assimilated [21, 24–27] into the land surface models. Among them, surface albedo from the moderate resolution imaging spectroradiometer (MODIS) [18, 24–34] is one of the most widely used products. Unfortunately, for most of the assimilation methods [25–27, 31], the effect of the solar radiation partitioning [17, 35] is not included. In fact, the surface albedos for visible and near-infrared solar radiations are quite different

[17]; solar radiation partitioning is important to parameterize the surface albedo.

In this paper, the MODIS-retrieved direct visible, direct near-infrared, diffuse visible, and diffuse near-infrared surface albedos were assimilated into the integrated urban land model (IUM). The solar radiation partitioning method [17] was introduced to parameterize the surface albedo to consider the effect of the wavelength of the solar radiation. Based on the surface albedo data from MODIS and the solar radiation partitioning method, the surface albedo data set for the Beijing municipal area was generated. Based on the surface albedo data set and the IUM, the impacts of the surface albedo on surface radiation budget were discussed quantitatively.

2. Data and Method

2.1. Study Area. The study area of this paper is the Beijing municipal area. The research region is located at 39.3°–41.1°N, 115.2°–117.6°E. The terrain tilts from northwest to southeast (Figure 1(a)). The dominate land cover

FIGURE 1: (a) Shaded relief elevation above sea level (m) and the position of the 325 m tower; (b) USGS LUCs based on MODIS (1, urban and built-up land; 2, dryland cropland and pasture; 3, irrigated cropland and pasture; 4, mixed dryland/irrigated cropland and pasture; 5, cropland/grassland mosaic; 6, cropland/woodland mosaic; 7, grassland; 8, shrubland; 9, mixed shrubland/grassland; 10, savanna; 11, deciduous broadleaf forest; 12, deciduous needleleaf forest; 13, evergreen broadleaf forest; 14, evergreen needleleaf forest; 15, mixed forest; 16, water bodies; 17, herbaceous wetland; 18, wooded wetland; 19, barren or sparsely vegetated).

category (LUC) in each grid is based on MODIS 1 km resolution data in 2017 (Figure 1(b)). The LUCs were transferred from International Geosphere-Biosphere Programme (IGBP) classification to United States Geological Survey (USGS) classification using the relationship listed in Table 1. The Chinese Academy of Sciences 325-m-high Meteorology and Environmental Observation Tower (325 m tower) was located in downtown Beijing, and the longitude and latitude of the 325 m tower are 116.37 E and 39.97 N, respectively (Figure 1(a)).

2.2. Data. The 325 m tower data were used for the surface albedo data comparison. The tower is located in downtown Beijing, and the altitude of the foot of the tower is 49 m. The radiation fluxes including the upward and downward shortwave and longwave radiation are measured using the radiometer at the 47-meter height. The time ranges of the observed upward and downward shortwave radiation are from March to October 2018. The observed surface albedo is calculated as follows:

$$\alpha = \frac{S_{\uparrow}}{S_{\downarrow}}, \quad (1)$$

where α is the surface albedo; $S_{\uparrow}$ is the upward shortwave radiation (W m^{-2}); and $S_{\downarrow}$ is the downward shortwave radiation (W m^{-2}).

The albedos for direct visible, direct near-infrared, diffuse visible, and diffuse near-infrared solar radiations are from MODIS in 2015. The temporal and spatial resolution of the MODIS albedo data are 8d and 1 km, respectively. The MODIS albedo products were spliced and

clipped firstly; then, they were interpolated linearly from 8d to 1d.

The atmospheric forcing data used to drive the land surface model are originated from the Global Land Data Assimilation System (GLDAS) [36]. The initial field data are also originated from GLDAS. The temporal resolution of GLDAS is 3 h. The spatial resolution of GLDAS data is 0.25° , which was interpolated to 1 km by using a bilinear interpolation method.

2.3. Land Model. We employed the integrated urban land model (IUM) [37] to study the impact of the surface albedo on radiation budget. IUM was developed based on the common land model (CoLM) [38]. IUM integrates the land surface models for urban and natural land surfaces.

2.4. Surface Albedo Parameterization. The surface albedo for bare soil [15] in the IUM could be described as follows:

$$\begin{aligned} \alpha_{\text{vis,soil}} &= 0.22 \times [1 + \exp(-0.15 \times h_{\theta})] - 0.45 \times \theta, \\ \alpha_{\text{nir,soil}} &= 0.26 \times [1 + \exp(-0.15 \times h_{\theta})] - 0.45 \times \theta, \end{aligned} \quad (2)$$

$$\alpha_{\text{soil}} = \frac{(\alpha_{\text{vis,soil}} + \alpha_{\text{nir,soil}})}{2},$$

where h_{θ} is the solar elevation angle ($^\circ$); θ is the volumetric soil moisture; $\alpha_{\text{vis,soil}}$ and $\alpha_{\text{nir,soil}}$ are the albedos for visible and near-infrared solar radiations, respectively; and α_{soil} is the albedo for bare soil. The surface albedo for urban in the IUM could be described as follows:

TABLE 1: Land use and land cover (LULC) mapping between the IGBP and the USGS classifications.

LULC type	IGBP ID	USGS ID
Water	0	0
Evergreen needleleaf forest	1	14
Evergreen broadleaf forest	2	13
Deciduous needleleaf forest	3	12
Deciduous broadleaf forest	4	11
Mixed forest	5	15
Closed shrublands	6	8
Open shrublands	7	8
Woody savannas	8	10
Savannas	9	10
Grasslands	10	7
Permanent wetlands	11	18
Croplands	12	4
Urban and built-up	13	1
Cropland/natural vegetation mosaic	14	6
Snow and ice	15	24
Barren or sparsely vegetated	16	19

FIGURE 2: Monthly (a) and seasonal (b) average surface albedo simulations before and after assimilation and the observations.

$$\begin{aligned}
\alpha_{\text{vis,urb}} &= 0.15 \times [1 + \exp(-0.15 \times h_\theta)] - 0.45 \times \theta, \\
\alpha_{\text{nir,yrb}} &= 0.3 \times [1 + \exp(-0.15 \times h_\theta)] - 0.45 \times \theta, \\
\alpha_{\text{urb}} &= \frac{(\alpha_{\text{vis,urb}} + \alpha_{\text{nir,urb}})}{2},
\end{aligned} \tag{3}$$

where $\alpha_{\text{vis,urb}}$ and $\alpha_{\text{nir,urb}}$ are the albedos for visible and near-infrared solar radiations, respectively, and α_{urb} is the albedo for urban. The surface albedo for vegetated surfaces is the same as that in the CoLM. A two-stream approximation method is used to parameterize it. The grid point surface albedo is calculated as follows:

$$\alpha = \alpha_{\text{soil}} \times f_{\text{soil}} + \alpha_{\text{urb}} \times f_{\text{urb}} + \alpha_{\text{veg}} \times f_{\text{veg}}, \tag{4}$$

where α_{veg} is the albedo for vegetation and f_{soil} , f_{urb} , and f_{veg} are the fractional cover for soil, urban, and vegetation, respectively.

In this paper, the moderate resolution imaging spectroradiometer- (MODIS-) retrieved direct visible, direct near-infrared, diffuse visible, and diffuse near-infrared surface albedos were assimilated into the integrated urban land model (IUM). The solar radiation partitioning method was introduced to parameterize the surface albedo. The assimilation algorithm is as follows:

$$\alpha = R_{\text{dv}} \times \alpha_{\text{vis,dif}} + R_{\text{dn}} \times \alpha_{\text{nir,dif}} + R_{\text{fv}} \times \alpha_{\text{vis,dif}} + R_{\text{fn}} \times \alpha_{\text{nir,dif}}, \tag{5}$$

where R_{dv} , R_{fv} , R_{dn} , and R_{fn} are direct visible, diffuse visible, direct near-infrared, and diffuse near-infrared solar radiations (W m^{-2}), respectively; they are calculated based on Weiss and Norman [35] and corrected to consider the effect of cloud cover [17]. $\alpha_{\text{vis,dif}}$, $\alpha_{\text{nir,dif}}$, $\alpha_{\text{vis,dif}}$, and $\alpha_{\text{nir,dif}}$ are albedos for direct visible, direct near-infrared, diffuse visible, and diffuse near-infrared

TABLE 2: Biases between the monthly average surface albedo simulations before and after assimilation and the observations (simulation minus observation).

Month	Bias/old	Bias/new
March	-0.022	-0.003
April	-0.025	-0.001
May	-0.026	-0.011
June	-0.023	0.001
July	-0.026	-0.019
August	-0.017	-0.004
September	-0.008	0.0002
October	-0.014	-0.004

FIGURE 3: Continued.

FIGURE 3: Spatial distribution of the annual (e) and seasonal (a–d) average surface albedo simulations before assimilation in the Beijing municipal area.

FIGURE 4: Continued.

FIGURE 4: Spatial distribution of the annual (e) and seasonal (a–d) average surface albedo simulations after assimilation in the Beijing municipal area.

solar radiations, respectively; they are retrieved from MODIS. The surface albedo data set for the Beijing municipal area was generated based on the assimilation algorithm and MODIS data. The spatial and temporal resolution of the surface albedo data are 1 km and 1d, respectively.

3. Results and Discussion

First, in order to validate the accuracy of the surface albedo simulations before and after assimilation, we compared them with the observed surface albedos in the 325 m tower site. Figures 2(a) and 2(b) are the monthly and seasonal average surface albedo simulations before and after assimilation and the observations. The biases between the monthly average surface albedo simulations before and after assimilation and the observations are listed in Table 2. In the whole assimilation period, after assimilation, the albedo simulations are larger than those before assimilation. After assimilation, the biases are decreased apparently for all the months and seasons compared with those before assimilation.

Then, we compared the spatial distribution of the annual and seasonal average surface albedo simulations before (Figure 3) and after (Figure 4) assimilation in the Beijing municipal area. The differences (after assimilation minus before assimilation) between the simulation results before and after assimilation are plotted in Figure 5. For urban areas, the surface albedo simulations after assimilation are usually larger than those before assimilation. However, for other LUCs, the surface albedo simulations after assimilation are usually smaller than those before assimilation.

Then, we compared the annual and seasonal average surface albedo simulations before and after assimilation for different LUCs. Here, to simplify the comparison, we

merged the LUCs of the research region into four main LUCs, that is, urban, cropland, forest, and grassland (Table 3). For most of the urban areas, the annual average surface albedo simulations after assimilation are larger than those before assimilation (Figure 6). However, for cropland, grassland, and forest areas, the annual average surface albedo simulations after assimilation are smaller than those before assimilation (Figure 6). Positive correlations exist for all the four LUCs, and the correlation coefficients between the simulations before and after assimilation for urban, cropland, grassland, and forest LUCs are 0.447, 0.182, 0.557, and 0.570, respectively.

We also compared the monthly average surface albedos for these four LUCs (Figure 7). For urban areas, the surface albedo simulations after assimilation are larger than those before assimilation for all the 12 months. However, for cropland, grassland, and forest areas, the surface albedo simulations after assimilation are smaller than those before assimilation for all the 12 months. For cropland, grassland, and forest areas, the surface albedo simulations before assimilation are relatively small in summer and large in winter; on the contrary, the surface albedo simulations after assimilation are relatively large in summer and small in winter. For cropland, grassland, and forest areas, the surface albedo simulations before and after assimilation are relatively large in November because of the snowfall and December because of the snow cover (Figure 8).

Surface albedo is associated with the upward solar radiation, so it is a crucial parameter in surface radiation budget. Figure 9 is the monthly average net radiation simulations before and after assimilation for the four main LUCs. Figure 10 is the scatter plot of the annual average albedo and net radiation simulation differences before and after assimilation for the four main LUCs (after

FIGURE 5: Spatial distribution of the annual (e) and seasonal (a–d) average surface albedo simulation differences before and after assimilation in the Beijing municipal area (after assimilation minus before assimilation).

TABLE 3: Mapping for LUC merging.

LUC types	LUC types after combination
Urban and built-up land	Urban
Dryland cropland and pasture	Cropland
Irrigated cropland and pasture	Cropland
Mixed dryland/irrigated cropland and pasture	Cropland
Cropland/grassland mosaic	Cropland
Cropland/woodland mosaic	Cropland
Grassland	Grassland
Shrubland	Grassland
Mixed shrubland/grassland	Grassland
Savanna	Grassland
Deciduous broadleaf forest	Forest
Deciduous needleleaf forest	Forest
Evergreen broadleaf forest	Forest
Evergreen needleleaf forest	Forest
Mixed forest.	Forest

FIGURE 6: (a) Spatial average of the annual average albedo simulations before and after assimilation for the four main LUCs; (b) scatter plot of the annual average albedo simulations before and after assimilation for the four main LUCs.

FIGURE 7: Continued.

FIGURE 7: Spatial average of the monthly average albedo simulations before and after assimilation for the four main LUCs: (a) urban; (b) cropland; (c) grassland; (d) forest.

FIGURE 8: Spatial average of the monthly cumulative precipitation for the four main LUCs.

FIGURE 9: Continued.

FIGURE 9: Spatial average of the monthly average net radiation simulations before and after assimilation for the four main LUCs: (a) urban; (b) cropland; (c) grassland; (d) forest.

FIGURE 10: Scatter plot of the annual average albedo and net radiation simulation differences before and after assimilation for the four main LUCs (after assimilation minus before assimilation).

assimilation minus before assimilation). Albedo is inversely proportional to the net radiation. For urban areas, where the surface albedo simulations after assimilation are larger than those before assimilation, the net radiation simulations after assimilation are smaller than those before assimilation. However, for other LUCs, the net radiation simulations after assimilation are larger than those before assimilation.

Net radiation is not only associated with the upward solar radiation but also with the upward longwave radiation. As the upward longwave radiation is dependent on the surface radiative temperature, we compared the monthly average surface radiative temperature for these four LUCs (Figure 11). Figure 12 is the scatter plot of the annual average albedo and upward longwave radiation

simulation differences before and after assimilation for the four main LUCs (after assimilation minus before assimilation). Albedo is inversely proportional to the upward longwave radiation. As the solar albedo increases, the solar radiation received by the land decreases; as a result, the surface radiative temperature and the upward longwave radiation decrease too.

The monthly average surface radiation budget simulations before and after assimilation for the four LUCs are shown in Figure 13. A quantitative analysis was performed for the impacts of the surface albedo on the surface radiation budget (Table 4). For urban areas, compared with that before assimilation, after assimilation, the annual average net radiation decreases about 5.6%. For cropland, grassland, and forest areas, compared with those before assimilation, after

FIGURE 11: Spatial average of the monthly average surface radiative temperature simulations before and after assimilation for the four main LUCs: (a) urban; (b) cropland; (c) grassland; (d) forest.

FIGURE 12: Scatter plot of the annual average albedo and upward longwave temperature simulation differences before and after assimilation for the four main LUCs (after assimilation minus before assimilation).

FIGURE 13: Spatial average of the monthly average radiation budget simulations before and after assimilation for the four main LUCs: (a) urban; (b) cropland; (c) grassland; (d) forest.

assimilation, the annual average net radiations increase about 20.2%, 24.3%, and 18.7%, respectively.

4. Summary

In this paper, the MODIS-retrieved direct visible, direct near-infrared, diffuse visible, and diffuse near-infrared surface albedos were assimilated into the IUM. The solar radiation partitioning method was introduced to parameterize the surface albedo. Based on the albedo data from MODIS and the solar radiation partitioning method, the surface albedo data set for the Beijing municipal area was generated. The surface albedo data were validated in the 325 m tower which was located in downtown Beijing. The result indicates that, after assimilation, the simulation results of the surface albedo are improved apparently.

Surface albedo is a crucial parameter in the surface radiation budget. The results indicate that the surface albedo is inversely proportional to the net radiation. For urban areas, compared with that before assimilation, after assimilation, the annual average net radiation decreases about 5.6%. For cropland, grassland, and forest areas, compared with those before assimilation, after assimilation, the annual average net radiations increase about 20.2%, 24.3%, and 18.7%, respectively.

In the near future, the observed four components of the solar radiation should be used to validate the solar radiation partitioning methods. More observational sites should be used to validate the surface albedo data set. The generation algorithm of the surface albedo data set will be extended to a larger area such as the whole of China or the world.

TABLE 4: Simulated annual average upward solar radiation, upward longwave radiation, and net radiation for urban, cropland, grassland, and forest LUCs before and after assimilation.

Variables and LUCs		Before assimilation	After assimilation
S↑	Urban	16.9	21.7
	Cropland	37.3	25.0
	Grassland	38.6	23.5
	Forest	34.0	19.6
L↑	Urban	395.7	394.0
	Cropland	376.2	379.5
	Grassland	357.8	361.4
	Forest	363.9	368.6
Rn	Urban	53.5	50.5
	Cropland	45.0	54.1
	Grassland	47.3	58.8
	Forest	51.8	61.5

Data Availability

The observational data from the 325 m tower station are from the Institute of Atmospheric Physics, Chinese Academy of Sciences, and are available in the supplementary materials.

Conflicts of Interest

The author declares that there are no conflicts of interest.

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Supplementary Materials

The observational data from the Chinese Academy of Sciences 325 m-high Meteorology and Environmental Observation Tower (325 m tower) are provided as the Supplementary Materials. (*Supplementary Materials*)

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