Reconstruction of Historical Land Surface Albedo Changes in China From 850 to 2015 Using Land Use Harmonization Data and Albedo Look-Up Maps

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Abstract Land surface albedo is a critical parameter of the Earth’s energy budget and has been greatly altered by climate change and human activities. To improve our understanding of historical land surface albedo changes and their climatic effects before the satellite remote sensing era, we reconstructed land surface albedo in China from 850 to 2015 using the historical land use harmonization version 2 (LUH2) data set and albedo look-up maps, and estimated the radiative forcing induced by land surface albedo changes using atmospheric radiative kernels. The reconstruction results showed that the annual-mean land surface albedo in China increased by 0.00110 during 850–2015, and the rate of increase was accelerated by the expansion of croplands during recent centuries. The most significant increases in land surface albedo were found in the Huang-Huai-Hai (HHH; +0.00646) and Northeast China (NE; +0.00501), which were primarily driven by anthropogenic land cover transformations (e.g., land reclamation, deforestation, and urbanization) and can be enhanced by the vegetation masking effect on snow cover. The radiative forcing induced by land surface albedo changes in China during 850–2015 and 1750–2015 was $-0.09 \pm 0.04$ and $-0.06 \pm 0.02$ W m$^{-2}$, respectively, which indicated that the land surface albedo changes produced a slight climate cooling effect, helping to offset the warming effect caused by greenhouse gas emissions.

Plain Language Summary As an indicator for denoting the reflectance properties of land surfaces, albedo varies with land cover and geophysical properties. In the recent decades, the satellite observations have demonstrated that the land surface albedo on global and regional scales has been greatly altered by global climate change and human activities. However, because land surface albedo before the satellite era cannot be directly acquired by measurements, historical land surface albedo changes must be obtained using reconstructions and model simulations. Herein, we reconstructed the historical land surface albedo changes in China from 850 to 2015 using land use harmonization data and albedo look-up maps. We found that the land surface albedo in China increased by 0.00110 during 850–2015 due to anthropogenic land cover transformations (e.g., land reclamation, deforestation, and urbanization) and the vegetation masking effect on snow cover. The results indicated that the historical changes of land surface albedo in China produced a slight climate cooling effect, helping to offset the warming effect caused by greenhouse gas emissions.

1. Introduction

Land surface albedo, defined as the ratio between the reflected and incident shortwave solar radiation at the surface, is considered one of the critical parameters of the Earth’s energy budget (Liang et al., 2010; Trenberth et al., 2009). As an indicator for denoting the reflectance properties of land surfaces, albedo varies with land cover and geophysical properties (e.g., fraction of snow cover, greenness of vegetation, vegetation structure, surface roughness, and soil moisture). In recent decades, land surface albedo on global and regional scales has been greatly altered by global climate change and human activities (He et al., 2014; Li, Ma et al., 2018). The land surface albedo changes caused by anthropogenic land cover transformations are acknowledged as one of the leading factors contributing to global climate change (Hansen et al., 1997; Lejeune et al., 2017). It is therefore important to evaluate long-term land surface albedo changes and their climatic effects using measurements and models (Bright et al., 2015; Schwaiger & Bird, 2010).
In the satellite remote sensing era (1970s to present), the spatiotemporal variations of land surface albedo have been monitored by satellite observations (Qu et al., 2015). A variety of land surface albedo data sets were derived using remote-sensing data; these include the Global Land Surface Satellite (GLASS) (Liu et al., 2013; Qu et al., 2014, 2016), Cloud, Albedo, and Radiation (CLARA) (Carlsson et al., 2017; Riihela et al., 2013), Moderate Resolution Imaging Spectroradiometer (MODIS) (Schaaf et al., 2002; Wang et al., 2018), Visible Infrared Imaging Radiometer (VIIRS) (Liu et al., 2017; Wang et al., 2013), and Landsat data (He et al., 2018; Shuai et al., 2014). Recently, land surface albedo trends on global (He et al., 2014; Li, Ma et al., 2018) and regional scales (e.g., Loess Plateau (Zhai et al., 2015), Qinghai-Tibet Plateau (Li et al., 2014), Sanjiang Plain (Li et al., 2020), and northern China (Hu et al., 2019)) have been analyzed using these data sets. However, because land surface albedo before the satellite era cannot be directly acquired by measurements, historical land surface albedo changes must be obtained using reconstructions and model simulations (Boisier et al., 2007). Betts et al. (2007) simulated historical land surface albedo changes relative to the natural state with the Hadley Center Atmospheric Model version 3 (HadAM3) and found that the present-day global mean radiative forcing by anthropogenic surface albedo change is about −0.2 W m⁻² causing a cooling effect. Pongratz et al. (2009) estimated the radiative forcing induced by land surface albedo changes during the last 12 centuries (800–1992) with a population-based reconstruction of the Anthropogenic Land Cover Change data set. They found that the global mean radiative forcing had a magnitude less than −0.05 W m⁻² during the preindustrial period, and the time period 1800–1992 covers 79% of the changes in global mean radiative forcing of the last thousand years. Ghimire et al. (2014) reconstructed global land surface albedo changes from 1700 to 2005 using historical land use data and albedo look-up maps and found that global mean radiative forcing induced by land surface albedo changes from 1700 to 2005 was −0.15 ± 0.10 W m⁻² (mean ± standard deviation).

Because China is an ancient agricultural country with a long history, its land surface albedo changes as well as the radiative forcing induced by anthropogenic land cover transformations during the historical period should be thoroughly evaluated (Zheng et al., 2009). Zhai et al. (2014) reconstructed land surface albedo changes in China from 1990 to 2010 and found that the surface radiative forcing caused by land cover changes in China over the past two decades was about 0.062 W m⁻². Different ecological regions experienced different radiative effects; land surface albedo in the Beijing-Tianjin-Tangshan ecological region decreased by 0.00456 from 1990 to 2010, increasing surface radiative forcing by 0.863 W m⁻², while the albedo in the Sanjiang Plain temperate-humid agricultural and wetland ecological region increased by 0.00152 from 1990 to 2010, decreasing surface radiative forcing by −0.184 W m⁻². Zhang et al. (2012) simulated historical land surface albedo changes caused by agricultural development across Northeast China using the Weather Research and Forecasting (WRF) model; they found that the agricultural development over the last 300 years caused surface net radiative forcing in Northeast China Plain to increase by 4–8, 2–5, and 1–3 W m⁻² during spring, autumn, and winter, respectively.

To improve our understanding of historical land surface albedo changes and their climatic effects over the past 12 centuries, we reconstructed historical land surface albedo changes in China from 850 to 2015 using the historical land use data set and albedo look-up maps and estimated the top-of-atmosphere (TOA) radiative forcing with atmospheric radiative kernels. The results of this study are significant for improving our understanding of how historical land surface albedo changes contributed to global climate change. The results also provide information about historical land surface albedo changes prior to the satellite remote sensing era.

2. Materials and Methods

2.1. Study Area

The terrestrial area of modern China was selected as the study area and divided into nine agricultural zones (Figure 1) based on the cropping system and growth environment (Institute of Agricultural Resources and Regional Planning, 2018): (a) Northeast China (NE), (b) Inner Mongolia and regions along the Great Wall (IMGW), (c) Huang-Huai-Hai River Basins (HHH), (d) Loess Plateau area (LP), (e) Middle and Lower Reaches of the Yangtze River (MLRYR), (f) Southwest China (SW), (g) South China (SC), (h) Gansu-Xinjiang (GX), and (i) Qinghai-Tibetan (QT). Among these agricultural zones, the HHH, MLRYR, SC, NE, and parts of SW and LP are considered traditional agricultural areas; they are located in highly populous
and low-elevation eastern China. In contrast, the western part of China (IMGW, LP, GX, and QT) mainly consists of mountains, deserts, and plateaus, with low population density and high elevations. From 850 to 2015, China was mainly ruled by the Tang Dynasty (AD 618–907), the Five Dynasties and Ten Kingdoms (907–960), the Song Dynasty (960–1279), the Yuan Dynasty (1271–1368), the Ming Dynasty (1368–1644), the Qing Dynasty (1644–1911), the Republic of China (1912–1949), and the People's Republic of China (1949 to present).

2.2. Data

2.2.1. Historical Land Use Data

The Land Use Harmonization Version 2 (LUH2) data set was used to represent historical human land use activities in China from 850 to 2015. It is a new historical and projected future land-use forcing data set for the World Climate Research Program Coupled Model Intercomparison Project Phase 6 (CMIP6) (Eyring et al., 2016). LUH2 was developed based on the Historical Database of the Global Environment (HYDE).
(Goldewijk et al., 2017) and multiple future scenarios. It provides global gridded fractional land use patterns, underlying land use transitions, key agricultural management information, and resulting secondary lands data from 850 to 2100 with a spatial resolution of 0.25° × 0.25° and a temporal resolution of 1 year (Hurtt et al., 2020). In this study, only the historical land use data set from 850 to 2015 was employed. For each pixel, LUH2 contains land use information about 12 sub-grid scale land use types: forested primary land, non-forested primary land, potentially forested secondary land, potentially non-forested secondary land, managed pasture, rangeland, urban land, C3 annual cropland, C3 perennial cropland, C4 annual cropland, C4 perennial cropland, and C3 nitrogen-fixing cropland. For simplicity, the 12 land use types were merged into five broad land use types (primary land, secondary land, pasture, urban land, and croplands); a sixth LUH2 land use type for water/ice was computed as the fraction of each pixel not represented by any of the five broad LUH2 land use types.

2.2.2. Albedo Look-Up Maps

The albedo look-up maps derived by Gao et al. (2014) were used to estimate historical land surface albedo for each combination of land cover type, geographic location, month, illumination condition, and presence/absence of snow. Because land surface albedo varies with both land cover type and geographic location, a global geographic location and land cover type-related albedo data set for different conditions were needed. Gao et al. (2014) derived the hierarchical Bidirectional Reflectance Distribution Function (BRDF) and albedo look-up maps by applying the homogeneity test, multi-scale statistics, and hierarchical composite processes to a decade (2001–2011) of global gap-filled MODIS BRDF/albedo product. These albedo look-up maps provide the global gridded mean and standard deviation of land surface albedo (black-sky and white-sky albedo at visible, near infrared, and shortwave wavelengths) and BRDF data for different International Geosphere-Biosphere Programme (IGBP) land cover types, months, illumination conditions, and snow-covered/free scenarios at various spatial resolution levels (0.05, 0.075, 0.1, 0.15, 0.2, 0.25, 0.3, 0.4, 0.5, 0.75, 1, 1.5, 2, 3, 4, 5, 7.5, 10, and 360 degrees). When there is no associated MODIS-derived albedo value for a given historical land cover type in a high spatial resolution layer (i.e., 0.05°), it can be obtained by searching coarser layers until the albedo value becomes available. Gao et al. (2014) compared the reconstructed global land surface albedo with the MODIS albedo data product, and found the reconstructed results agree well with the satellite-derived albedo product (mean bias difference is within ±0.002 and R² is 0.915 for snow-free condition; mean bias difference is ~ ±0.002 and R² is 0.741 for snow-covered condition).

2.2.3. Other Auxiliary Data

To evaluate the reconstruction results of historical land surface albedo, the GLASS land surface albedo product (the data set derived from MODIS data with a spatial resolution of 0.05°, hereafter referred to as GLASS-MODIS data) from 2000 to 2015 was used as a reference. To determine the historical land cover changes in China, the MODIS IGBP land cover map (MCD12Q1) (Sulla-Menashe et al., 2019) from 2001 to 2005 with a 500-m horizontal resolution was also used in this study. The perennial (2001–2011) mean of the MODIS monthly snow cover global Climate Modeling Grid product (MOD10C1) with a spatial resolution of 0.05° × 0.05° (Hall et al., 2002) was used to determine the monthly snow covered/free scenarios. Because the spatial resolutions of the snow cover data differed from that of the LUH2 data, the snow cover data were aggregated to the spatial resolution of 0.25° × 0.25°. The perennial (1979–2020) mean of the European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis version 5 (ERA5) (Hersbach et al., 2020) monthly averaged solar radiation reanalysis data (surface total/direct downward shortwave radiation fluxes) with a spatial resolution of 0.25° was used to determine the fraction of diffuse/direct illumination for each pixel and month. Due to the unavailability of historical snow cover and illumination condition data, we assumed that the snow cover conditions and radiation fields were stationary over time. To test the influences of this assumption (see Text S1), the CMIP6 snow cover and surface shortwave radiation data were also used in this study. The first ensemble outputs (r1i1p1f1) of the Community Earth System Model-Finite Volume 2 (CESM2-FV2) model from 1850 to 2014 (historical experiment) were used. The variables of snc (surface snow area fraction), rsds (surface shortwave downward radiation), and rsdsdiff (surface shortwave downward diffuse radiation) were used for denoting the variations of snow cover and fraction of diffuse radiation from 1850 to 2014.

The atmospheric radiative kernels derived using the off-line Community Earth System Model-Community Atmosphere Model version 5 (CESM-CAMS) (Pendergrass et al., 2018) were employed to estimate the TOA
radiative forcing induced by land surface albedo changes. The atmospheric radiative kernels of CESM-CAM5 provide the information about the TOA and surface radiative forcing (change in radiation flux) for a 0.01 change in surface albedo and enable to approximate decomposition of the contributions to changes in radiative fluxes. Compared with the model simulations, the global mean error of the newly derived atmospheric radiative kernels for TOA shortwave clear-sky radiative response is 0.4 W m\(^{-2}\). Compared with the former atmospheric radiative kernels, the CESM-CAM5 can provide a more accurate estimation of TOA albedo radiative feedbacks (error within 0.2 W m\(^{-2}\) K\(^{-1}\)).

2.3. Methods

We reconstructed and estimated historical land surface albedo changes and their effects on radiative forcing using the following steps. First, we determined the historical land cover changes in China by mapping the LUH2 land use types to IGBP land cover types. Then, we reconstructed the historical land surface albedo changes with the historical land cover data and the albedo look-up maps. Finally, we estimated the radiative forcing based on the reconstructed historical land surface albedo data and atmospheric radiative kernels.

2.3.1. Determining Historical Land Cover Changes

Due to the inconsistency between LUH2 land use types and albedo look-up maps (IGBP land cover types), the LUH2 land use types must be mapped to the IGBP land cover types. The mean state (most frequently occurring land cover types for each pixel) of MODIS IGBP land cover map (MCD12Q1) from 2001 to 2005 with a 500 m horizontal resolution was used as the reference for this purpose. The MODIS IGBP land cover map was first aggregated to a spatial resolution of 0.25° × 0.25° and then used as a reference for converting the LUH2 land use types to IGBP land cover types with one-to-one and one-to-many mapping rules. The one-to-one and one-to-many mapping rules between LUH2 land use types and IGBP land cover types were applied following the methods used by Ghimire et al. (2014): (a) LUH2 urban lands were directly mapped to the IGBP urban and built-up lands; (b) LUH2 croplands were mapped to the IGBP croplands and croplands/natural vegetation mosaics; (c) LUH2 pasture was mapped to IGBP closed shrublands, open shrublands, woody savannas, savannas, and grasslands; (d) LUH2 primary and secondary lands were mapped to IGBP forest types (evergreen needleleaf forest, evergreen broadleaf forest, deciduous needleleaf forest, deciduous broadleaf forest, and mixed forests), closed shrublands, open shrublands, woody savannas, savannas, and grasslands; and (e) LUH2 water/ice was mapped to IGBP water bodies, wetlands, and snow and ice. Based on these mapping rules, the LUH2 land use types were mapped and converted according to the fractions of IGBP land cover types for each pixel. In this procedure, the mapping rules were assumed to be invariant. Historical land cover in China was therefore reconstructed by multiplying the fractions of LUH2 land use types in each pixel with the proportions of the matched IGBP land cover types.

2.3.2. Reconstruction of Historical Land Surface Albedo

Historical monthly land surface albedo in each pixel was reconstructed by weighted combination of the albedo look-up maps for different land cover types, snow-covered/free scenarios, and illumination conditions in that pixel (Ghimire et al., 2014; Jiao et al., 2017),

\[
\alpha_{m,y} = \sum_{l=0}^{17} \sum_{s=0}^{1} \sum_{r=0}^{1} f_{l,s,r} f_{s,m} f_{r,m} \alpha_{l,s,r,m},
\]

where \(\alpha_{m,y}\) is the reconstructed land surface albedo of a pixel for each month \((m)\) and year \((y)\); \(f_{l,s}\) is the fraction of a given land cover type \((l)\) at year \((y)\); \(f_{s,m}\) is the fraction of snow-covered \((s=0)\) and snow-free \((s=1)\) scenarios at month \((m)\); \(f_{r,m}\) is the fraction of diffuse \((r=0)\) and beam \((r=1)\) illumination conditions at month \((m)\); and \(\alpha_{l,s,r,m}\) is the mean value from albedo look-up maps for a given geographic location, land cover type \((l)\), snow-covered/free scenario \((s)\), illumination condition \((r)\), and month \((m)\). The monthly snow-covered/free scenario and illumination condition for each pixel were determined based on the perennial mean of MODIS snow cover and ERA5 solar radiation reanalysis data, respectively.

2.3.3. Estimation of Radiative Forcing Induced by Land Surface Albedo Changes

The TOA radiative forcing induced by land surface albedo changes was estimated using the atmospheric radiative kernels (Jiao et al., 2017),
where $F_{m,y}$ is the TOA radiative forcing induced by the land surface albedo changes at month ($m$) and year ($y$); $\Delta \alpha_{m,y,bs}$ and $\Delta \alpha_{m,y,ws}$ are the black-sky (bs) and white-sky (ws) albedo changes during month ($m$) and year ($y$), respectively, compared to the land surface albedo of a reference year (e.g., year 850 or 1750); $f_{r,m}$ is the fraction of diffuse ($r = 0$) and beam ($r = 1$) illumination conditions at month ($m$); and $K_{bs}$ and $K_{ws}$ are the atmospheric radiative kernels for black-sky and white-sky albedo, respectively. In this study, the mean radiative forcing values were estimated using the mean albedo values from the albedo look-up maps, and the radiative forcing uncertainties were estimated using the standard derivation of albedo values from the albedo look-up maps.

3. Results

3.1. Evaluation of the Reconstructed Land Surface Albedo

To evaluate the efficiency of historical reconstruction method, we compared our reconstructed results with the satellite-derived GLASS-MODIS data from 2000 to 2015. The comparison results (Figure 2) show that the spatial patterns and temporal variations of our reconstructed results and GLASS-MODIS data were quite similar and comparable ($R^2$ is 0.950 and mean bias difference is 0.015). The differences between these two data sets were mainly due to the variation of snow cover and different algorithms to generate spatio-temporal continuous datasets. However, the reconstruction of historical land surface albedo can reveal the major trends of human-induced land surface albedo changes under invariant snow cover scenarios, the accuracy of which does not suffer from differences between reconstructed and satellite-derived albedo, but mainly depend on the uncertainties of LUH2 land use data and albedo look-up maps.

3.2. Historical Land Cover Changes in China

The reconstructed IGBP land cover changes in China from 850 to 2015 are shown in Figure 3. The fraction of IGBP croplands (from 1.51% to 10.37%), croplands/natural vegetation mosaics (from 0.27% to 2.13%), and urban and built-up lands (from less than 0.01% to 0.61%) increased significantly over the past millennium, while the fraction of grasslands decreased (from 37.28% to 32.68%) due to land reclamation. Savannas (from 13.24% to 9.77%), deciduous broadleaf forests (from 4.29% to 3.16%), and woody savannas (from 10.98% to 10.16%) also decreased between 850 and 2015.

The spatial patterns of historical land cover changes in China from 850 to 2015 are shown in Figure 4. Eastern China experienced a substantial decreasing trend in forests (IGBP types of evergreen needleleaf forests, evergreen deciduous forests, deciduous needleleaf forest, deciduous broadleaf forests, and mixed forests) and grasslands, along with an increasing trend in croplands (IGBP types of croplands and croplands/natural vegetation mosaics) and urban areas. The most significant decreases in forests were found in NE (from 33.71% to 26.23%), SC (from 24.57% to 17.64%), LP (from 11.44% to 6.51%), MLRYR (from 18.97% to 15.12%), and SW (from 19.45% to 15.87%), while the most significant decreases in grasslands were found in HHH (from 37.28% to 32.68%) due to land reclamation. Savannas (from 13.24% to 9.77%), deciduous broadleaf forests (from 4.29% to 3.16%), and woody savannas (from 10.98% to 10.16%) also decreased between 850 and 2015.

3.3. Historical Land Surface Albedo Changes in China

The annual and seasonal mean land surface albedo and fraction of croplands (IGBP types of croplands and croplands/natural vegetation mosaics) in China from 850 to 2015 are shown in Figures 5 and S1. The
reconstructed results showed that the annual-mean land surface albedo in China increased from 0.20667 to 0.20777 (difference of 0.00110) during 850–2015. The evolution of historical land surface albedo in China can be largely characterized by five phases of development. In the first phase (between the 9th and 10th centuries), the land surface albedo remained nearly stable (∼0.20667). China was mainly dominated by the Tang Dynasty, the Five Dynasties and Ten Kingdoms, and the Song Dynasty during this period. The second phase of development was a rapid increase in land surface albedo during the 11th and 12th centuries. After the Chanyuan Treaty was signed in 1005 (Li, He, Li et al., 2018), land surface albedo increased significantly due to the recovery and development of agriculture after the war between the Song and Liao Dynasties. During the war between the Song and Jin Dynasties (1125–1234), large numbers of people migrated from northern China to southern China, which increased in the fraction of cropland in southern China. In the third phase (between the 13th and 14th centuries), annual mean land surface albedo decreased due to the wars between the Song, Jin, and Yuan Dynasties, as well as the damage and destruction of the agriculture-based economy during the period of the Yuan Dynasty (Li, He, Yang et al., 2018). The fourth phase was a period
of increasing land surface albedo during the Ming Dynasty and early Qing Dynasty (between the 15th and 17th centuries). The fraction of croplands increased with the recovery and expansion of agriculture that accompanied population growth. The fifth phase was another period of increasing land surface albedo that lasted from the early 18th century to the present. Since the era of the Qianlong Emperor of the Qing Dynasty (1735–1796), land surface albedo increased at a much higher rate (+0.00031/century) than during earlier periods. The 20th century witnessed the most rapid land surface albedo change (+0.00060/century) in the historical record. The rapid population growth of China during the last 300 years (He et al., 2015) spurred much larger reclamation activities compared to earlier centuries. The most significant land reclamation occurred in the NE region (Ye et al., 2009), which led to a dramatic increase of land surface albedo in NE during the last 300 years. The peak values of land surface albedo (0.20785) occurred in 2004. From 2004 to the present, the land surface albedo and fraction of croplands decreased, primarily due to China’s “Grain for Green” program and other afforestation programs (Chen et al., 2019; Uchida et al., 2005).

The spatial patterns of annual and seasonal mean land surface albedo changes in China between 850 and 2015 are shown in Figures 6 and S2. Land surface albedo showed substantial increasing trends in HHH (+0.00646) and NE (+0.00501); gradual increasing trends in LP (+0.00194), SC (+0.00081), and QT (+0.00064); and small to negligible trends in SW (+0.00023), MLRYR (+0.00024), GX (+0.00001), and IMGW (−0.00010). Significant increases in land surface albedo occurred in the northern and eastern part of Songnen Plain, the Lesser Khingan Mountains, Sanjiang Plain, Huabei Plain, Yili River Valley, and the eastern part of Qinghai-Tibet Plateau. These increases were mainly caused by deforestation, land reclamation, and urbanization. Huabei Plain was one of the most important agricultural areas in ancient China, and the area of cropland there expanded significantly during the last millennium to meet the needs of a growing population (Zheng et al., 2009). During the last 300 years, a large amount of land reclamation and deforestation occurred in NE as a result of the large-scale “Chuang Guandong” (migration during the 19th and 20th centuries) (Yang et al., 2017), as well as land reclamation in Heilongjiang Province (the “Great Northern Wilderness”) during the mid-20th century (Liu et al., 2014). Additionally, the increases of land surface albedo were enhanced by the vegetation masking effect on snow cover (Abe et al., 2017; Essery, 2013), which exhibited much stronger increasing trends over northern China. The most significant decreases in land surface albedo occurred in the central Songnen Plain, the farming-pastoral ecotone of China, the Sichuan Basin, and the lower reaches of the Yangtze River. These declines were mainly caused by converting grasslands to croplands.

### 3.4. Radiative Forcing Induced by Land Surface Albedo Changes

Between 850 and 2015, land surface albedo changes in China caused an annual mean TOA radiative forcing of −0.09 ± 0.04 W m⁻² (Figure 7a; the land surface albedo in 850 was used as a reference), generating a slight
cooling effect. The most significant radiative forcing effect occurred in HHH (−0.68 ± 0.31 W m$^{-2}$), followed by NE (−0.26 ± 0.06 W m$^{-2}$), LP (−0.19 ± 0.01 W m$^{-2}$), SC (−0.10 ± 0.02 W m$^{-2}$), QT (−0.08 ± 0.01 W m$^{-2}$), and MLRYR (−0.05 ± 0.13 W m$^{-2}$). The radiative forcing in SW (−0.03 ± 0.08 W m$^{-2}$), GX (0.00 ± 0.01 W m$^{-2}$), and IMGW (0.02 ± 0.00 W m$^{-2}$) was negligible between 850 and 2015, indicating that the land surface albedo changes in these agricultural zones had no significant influence on the climate.

Land surface albedo changes in China have also produced a slight cooling effect when radiative forcing is examined relative to values at the beginning of the Industrial Revolution (1750). Compared to 1750, the 2015 annual mean radiative forcing was −0.06 ± 0.02 W m$^{-2}$ (Figure 7a). The most significant radiative forcing occurred in NE (−0.21 ± 0.06 W m$^{-2}$), followed by HHH (−0.21 ± 0.09 W m$^{-2}$), LP (−0.08 ± 0.01 W m$^{-2}$), SC (−0.08 ± 0.00 W m$^{-2}$), QT (−0.07 ± 0.01 W m$^{-2}$), and SW (−0.04 ± 0.04 W m$^{-2}$). The annual and seasonal radiative forcing induced by land surface albedo changes in China during 850–2015 are shown in Figure 7b. The most significant radiative forcing in NE occurred during winter (−0.74 ± 0.06 W m$^{-2}$), followed by the spring (−0.18 ± 0.05 W m$^{-2}$), autumn (−0.17 ± 0.07 W m$^{-2}$), and summer (+0.04 ± 0.07 W m$^{-2}$).
This phenomenon indicates that the vegetation-masking effect on snow cover played an important role in radiative forcing over northern China.

4. Discussion and Conclusions

Our results imply that historical land surface albedo changes in China had a slight cooling effect on the global climate (−0.09 ± 0.04 and −0.06 ± 0.02 W m$^{-2}$ during 850–2015 and 1750–2015, respectively), which helped to offset the warming effect caused by greenhouse gas emissions (Schwaiger & Bird, 2010). In a previous study (Ghimire et al., 2014), the global radiative forcing induced by land surface albedo changes was estimated to be −0.15 ± 0.10 W m$^{-2}$. Our results are comparable to results from other previous studies (Betts et al., 2007; Jiao et al., 2017; Pongratz et al., 2009). The main contributions from this study are as follows: (a) LUH2 data allowed us to extend the analysis back to 850 (Hurtt et al., 2011, 2020), thereby enabling the reconstruction of land surface albedo changes before the industrial era; (b) the spatial resolution of the land use data set was significantly improved (0.25°) compared to previous studies (Betts et al., 2007; Ghimire et al., 2014), which enabled us to derive spatial patterns of historical land surface albedo changes with higher spatial resolution; and (c) newly derived atmospheric radiative kernels (Pendergrass et al., 2018) based on CESM-CAM5 were used to estimate the radiative forcing induced by land surface albedo changes. These new radiative kernels provide estimates of radiative forcing with higher accuracy.

Our reconstruction results showed that the historical land surface albedo in China increased by 0.00110 between 850 and 2015, and the albedo changes induced by anthropogenic land cover transformations (land reclamation, deforestation, and urbanization) can be further enhanced by the vegetation masking effect on snow cover. In northern China, the seasonal snow cover plays an important role in land surface albedo. There are large differences in surface albedo between the snow-covered and snow-free land surfaces (Figure 8). It can be seen that the increase in land surface albedo of snow-covered low stature vegetation (e.g., grasslands and croplands) was much larger than that of snow-covered high stature vegetation (e.g., forests). When the land cover type was converted from forests to croplands, the fraction of snow exposure during wintertime increased (Abe et al., 2017; Essery, 2013), causing a negative radiative forcing. For example, the strong negative radiative forcing in Northeast China (NE) was primarily caused by land reclamation and deforestation (Ye et al., 2009), which cause snow cover during winter to have a higher fractional exposure area and longer duration.
There are several issues and potential limitations concerning historical land surface albedo reconstruction that must be improved in the future. The topographic effects have great influences on land surface albedo over rugged terrain, and simply neglecting the topographic effects in the land surface albedo modeling can lead to large biases and uncertainties (Hao et al., 2018, 2019; Proy et al., 1989). However, the topographic effects were not considered by the albedo look-up maps used in this study. To overcome this limitation, an updated version of albedo look-up maps needs to be implemented in future studies. The uncertainties of reconstructed land surface albedo and estimated radiative forcing are largely connected with the accuracy of historical land use data. However, discrepancies in cropland quantities have been reported between the HYDE data, which were used to generate LUH2 and the Chinese historical cropland data set (CHCD) (He et al., 2013). Given these discrepancies, higher-accuracy and higher-confidence historical land use data in China are still required. Furthermore, in this study, land surface albedo in each pixel was assumed to have a temporally stable relationship with land cover type, fraction of IGBP types, snow-covered/free scenarios, and incident illumination conditions. However, these assumptions may cause inaccuracies in the reconstruction and estimation of land surface albedo. Because the look-up maps used in this study were derived based on MODIS data, the relationships between the land cover types and land surface albedo for a given

**Figure 6.** Spatial patterns of annual mean land surface albedo changes between 850 and 2015 in China.
pixel were validated using present-day conditions. However, if the regional climate changed dramatically, the land surface albedo inferred by land cover type could be unrealistic in certain situations. It has also been demonstrated that the snow cover extent and fraction of diffuse skylight in China varied in the recent decades (He & Wang, 2020; Tan et al., 2019). Especially, changes in snow cover extent can cause large differences in land surface albedo; they can also amplify land surface albedo changes caused by land cover type conversions (e.g., land reclamation, deforestation, and urbanization) (Li et al., 2020). The magnitude of the radiative forcing induced by land surface albedo changes may be underestimated if changes in snow cover are not considered (Zhai et al., 2014). We also performed an experiment using the CMIP6 snow cover

Figure 7. Radiative forcing induced by historical land surface albedo changes in China. (a) Annual radiative forcing induced by land surface albedo changes during 850–2015 and 1750–2015, and (b) annual and seasonal radiative forcing induced by land surface albedo changes in China during 850–2015. The bars and error bars stand for the mean values and standard derivations of estimated radiative forcing induced by land surface albedo changes, respectively.
and radiation data, and the results demonstrated that the variations of snow cover have great impacts on land surface albedo changes (Text S1 and Figure S3). Thus, our results can be considered as the land cover transformations-induced surface albedo changes under the invariant snow cover scenarios. To obtain historical land surface albedo changes with higher accuracy, historical reconstruction methods that account for changes in climate should be explored in future studies.

Conflict of Interest
The authors declare no conflicts of interest relevant to this study.

Data Availability Statement
The LUH2 historical land use data set can be downloaded from https://luh.umd.edu. The MODIS IGBP land cover map (MCD12Q1) data can be downloaded from https://lpdaac.usgs.gov/products/mcd12q1v006/. The MODIS monthly snow cover (MOD10C1) data can be downloaded from https://nsidc.org/data/MOD10C1/versions/5. The GLASS-MODIS land surface albedo product can be downloaded from http://glass.umd.edu/Albedo/MODIS/0.05D/. The ERA5 surface downward solar flux reanalysis data can be downloaded from https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels-monthly-means?tab=overview. The CMIP6 data can be downloaded from https://esgf-node.llnl.gov/projects/cmip6. The CAM5 atmospheric kernel data can be downloaded from https://zenodo.org/record/997902. The reconstructed annual mean land surface albedo in China from 850 to 2015 can be downloaded from https://zenodo.org/record/4892913.

References
Abe, M., Takata, K., Kawamiya, M., & Watanabe, S. (2017). Vegetation masking effect on future warming and snow albedo feedback in a boreal forest region of northern Eurasia according to MIROC-ESM. Journal of Geophysical Research: Atmospheres, 122(17), 9245–9261. https://doi.org/10.1002/2017JD026657

Figure 8. Snow-covered and snow-free white-sky albedo of different land cover types in January (the monthly albedo statistics in China were derived based on the albedo look-up maps).
Liang, S., Wang, K., Zhang, X., & Wild, M. (2010). Review on estimation of land surface radiation and energy budgets from ground measurement, remote sensing and model simulations. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 3*(3), 225–240. https://doi.org/10.1109/jstars.2010.2048556

Liu, Q., Wang, L., Qu, Y., Liu, N., Tang, H., Liang, S., & Liu, S. (2013). Preliminary evaluation of the long-term GLASS albedo product. *International Journal of Digital Earth, 6*(suppl), 5–33. https://doi.org/10.1080/17538947.2013.804001

Liu, X., Zhang, F., & Lo, K. (2014). Urbanization in remote areas: A case study of the Heilongjiang Reclamation Area, Northeast China. *Habitat International, 42*, 103–110. https://doi.org/10.1016/j.habitatint.2013.11.003

Liu, Y., Wang, Z., Sun, Q., Erh, A. M., Li, Z., Schaaf, C. B., et al. (2017). Evaluation of the VIIRS BRDF, Albedo and NBAR products suite and an assessment of continuity with the long term MODIS record. *Remote Sensing of Environment, 201*, 256–274. https://doi.org/10.1016/j.rse.2017.09.020

Pendergrass, A. G., Conley, A., & Vitt, F. M. (2018). Surface and top-of-atmosphere radiative feedback kernels for CESM-CAM5. *Earth System Science Data, 10*(1), 317–324. https://doi.org/10.5194/essd-10-317-2018

Pongratz, J., Raddatz, T., Reich, C. H., Eich, M., & Claussen, M. (2009). Radiative forcing from anthropogenic land cover change since A.D. 800. *Geophysical Research Letters, 36*, L02709. https://doi.org/10.1029/2008gl036394

Proy, C., Tanré, D., & Deschamps, P. Y. (1989). Evaluation of topographic effects in remotely sensed data. *Remote Sensing of Environment, 30*(1), 21–32. https://doi.org/10.1016/0034-4257(89)90044-8

Qu, Y., Liang, S., Liu, Q., He, T., Liu, S., & Li, X. (2015). Mapping surface broadband albedo from satellite observations: A review of literatures on algorithms and products. *Remote Sensing, 7*(1), 990–1020. https://doi.org/10.3390/rs71010990

Qu, Y., Liang, S., Liu, Q., Li, X., Feng, Y., & Liu, S. (2016). Estimating shortwave Arctic sea-ice albedo from MODIS data. *Remote Sensing of Environment, 186*, 32–46. https://doi.org/10.1016/j.rse.2016.08.015

Qu, Y., Liu, Q., Liang, S., Wang, L., Liu, N., & Liu, S. (2014). Direct-estimation algorithm for mapping daily surface-broadband albedo from MODIS data. *IEEE Transactions on Geoscience and Remote Sensing, 52*(2), 907–919. https://doi.org/10.1109/tgrs.2013.2245670

Riihelä, A., Manninen, T., Laine, V., Andersson, K., & Kaspar, F. (2013). CLARA-SAL: A global 28yr time series of Earth’s black-sky surface albedo. *Atmospheric Chemistry and Physics, 13*(7), 3743–3762. https://doi.org/10.5194/acp-13-3743-2013

Schaaf, C., Gao, F., Strahler, A., Lucht, W., Li, X., Tsang, T., et al. (2002). First operational BRDF, albedo nadir reflectance products from MODIS. *Remote Sensing of Environment, 83*(1-2), 135–148. https://doi.org/10.1016/s0034-4257(02)00091-3

Schwaiger, H. P., & Bird, D. N. (2010). Integration of albedo effects caused by land use change into the climate balance: Should we still account in greenhouse gas units? *Forest Ecology and Management, 260*(3), 278–286. https://doi.org/10.1016/j.foreco.2009.12.002

Shuai, Y., Maskel, J. G., Gao, F., Schaaf, C. B., & He, T. (2014). An approach for the long-term 30-m land surface snow-free albedo retrieval from historic Landsat surface reflectance and MODIS-based a priori anisotropy knowledge. *Remote Sensing of Environment, 152*, 467–479. https://doi.org/10.1016/j.rse.2014.07.009

Sulla-Menashe, D., Grey, J. M., Abercrombie, S. P., & Firiedl, M. A. (2019). Hierarchical mapping of annual global land cover 2001 to present: The MODIS Collection 6 Land Cover product. *Remote Sensing of Environment, 222*, 183–194. https://doi.org/10.1016/j.rse.2018.12.013

Tan, X., Wu, Z., Mu, X., Gao, P., Zhao, G., Sun, W., & Gu, C. (2019). Spatiotemporal changes in snow cover over China during 1960-2013. *Atmospheric Research, 218*(1), 183–194.

Trenberth, K. E., Fasullo, J. T., & Kiehl, J. (2009). Earth’s global energy budget. *Bulletin of the American Meteorological Society, 90*(3), 311–324. https://doi.org/10.1175/2008bams2634.1

Uchida, E., Xu, J., & Rozelle, S. (2005). Grain for Green: Cost-Effectiveness and Sustainability of China’s Conservation Set-Aside Program. *Land Economics, 81*(2), 247–264. https://doi.org/10.3368/le.81.2.247

Wang, D., Liang, S., He, T., & Yu, Y. (2013). Direct estimation of land surface albedo from VIIRS data: Algorithm improvement and preliminary validation. *Journal of Geophysical Research: Atmospheres, 118*, 12577–12586. https://doi.org/10.1002/2013jd020417

Wang, Z., Schaaf, C. B., Sun, Q., Shuai, Y., & Román, M. O. (2018). Capturing rapid land surface dynamics with Collection V006 MODIS BRDF/NBAR/Albedo (MCD43) products. *Remote Sensing of Environment, 207*, 50–64. https://doi.org/10.1016/j.rse.2018.02.001

Yang, Y., Zhang, S., Liu, Y., Xing, X., & Sherbinin, A. D. S. (2017). Analyzing historical land use changes using a Historical Land Use Reconstruction Model: A case study in Zhenlai County, northeastern China. *Scientific Reports, 7*, 41275. https://doi.org/10.1038/srep41275

Ye, Y., Fang, X., Ren, Y., Zhang, X., & Chen, L. (2009). Cropland cover change in Northeast China during the past 300 years. *Science in China-Series D: Earth Sciences, 52*(2), 1172–1182. https://doi.org/10.1007/s11430-009-0118-8

Zhai, J., Liu, R., Liu, J., Huang, L., & Qin, Y. (2015). Human-induced landcover changes drive a diminution of land surface albedo in the Loess Plateau (China). *Remote Sensing, 7*(3), 2926–2941. https://doi.org/10.3390/rs7032926

Zhai, J., Liu, R., Liu, J., Zhao, G., & Huang, L. (2014). Radiative forcing over China due to albedo change caused by land cover change during 1990-2010. *Journal of Geographical Sciences, 24*(5), 785–801. https://doi.org/10.1007/s11442-014-1120-4

Zhang, X., Wang, W., Fang, X., Ye, Y., & Zheng, J. (2012). Agriculture development-induced surface albedo changes and climatic implications across northeastern China. *Chinese Geographical Science, 22*(3), 264–277. https://doi.org/10.1016/j.rse.2017.09.020

Zheng, J., Lin, S., & He, F. (2009). Recent progress in studies on land cover change and its regional climatic effects over China during historical times. *Advances in Atmospheric Sciences, 26*, 793–802. https://doi.org/10.1007/s00376-009-9031-5