Evaluating the impacts of land use and land cover changes on surface air temperature using the WRF-mosaic approach

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Satellite-derived land surface data in 1980 and 2010 were used to represent land use and land cover (LULC) changes caused by the rapid economic development and human activities that have occurred over the past few decades in East Asia and China. The effects of LULC changes on the radiation budget and 2-m surface air temperature (SAT) were explored for the period using the Weather Research and Forecasting (WRF) model. The mosaic approach, which considers the N-most abundant land use types within a model grid cell (here, N = 3) and precisely describes the subgrid-scale LULC changes, was adopted in the integrations. The impacts of LULC changes based on two 36-year integrations showed that SAT generally decreased, with the sole exception being over eastern China, resulting in decreased SAT in China (−0.062 °C) and East Asian land areas (EAL, −0.061 °C). The LULC changes induced changes in albedo, which influenced the radiation budget. The radiative forcings at the top of the atmosphere were −0.56 W m⁻² across the whole of China, and −0.50 W m⁻² over EAL. Meanwhile, the altered roughness length mainly influenced near-surface wind speeds, large-scale and upward moisture fluxes, latent heat fluxes, and cloud fractions at different altitudes. Though the impacts caused by the LULC changes were generally smaller at regional scales, the values at local scales were much stronger.

1. Introduction

Land use and land cover (LULC) changes impact the energy and water exchange between the land surface and the atmosphere by altering the albedo and surface roughness, which in turn impacts the regional climate (Brovkin et al. 2009; Charney 1975; Fu 2003; Pitman et al. 2004). An estimated 42%–68% of the global land surface changed between 1700 and 2000, mainly in the Northern Hemisphere (Klein 2001; Food and Agriculture Organization (FAO) 2012). In the past few decades, because of rapid economic development and natural and anthropogenic activities, the LULC changes in China have shown different characteristics for individual land use categories, such as deforestation, afforestation, grassland degradation, urbanization, and other processes (Liu and Buheasier 2000; Liu et al. 2009). The LULC data of the past few decades, which reflects the dynamic variations of the land surface over China and East Asia, are essential for simulating and evaluating the impacts of LULC changes on the long-term regional climate.

In terms of the LULC changes, correctly expressing the radiation budget is important for evaluating the impacts on 2-m surface air temperature (SAT) and detecting the underlying physical mechanisms at work. Studies of global radiative forcing (RF) from LULC changes have improved, as reflected by increases in confidence levels, from the second through the fifth assessment reports of the IPCC (2013). However, considerable uncertainties remain.

Because of the heterogeneity of LULC, high-resolution regional climate models (RCMs) are useful for investigating
the impacts of LULC changes on regional climates (Gao et al. 2006). However, the default LULC data used in RCMs, such as the Weather Research and Forecasting (WRF) model (Skamarock et al. 2008) and the Fifth-Generation Penn State/National Center for Atmospheric Research Mesoscale Model (Grell, Dudhia, and Stauffer 1994), incorporate fixed values, which originate from satellite-derived images in 2001 (LU01) and 1992–1993 (LU92). It is believed that the LULC changes in the past few decades cannot be fully represented by these fixed values originating from LU01 or LU92 only. Although the default LULC data can be used for seasonal and annual studies, this approach is clearly unsuitable for decadal studies. High-quality, satellite-derived LULC data can therefore improve model performance at regional scales (Pielke et al. 1999; Sertel, Robock, and Ormeci 2009; Zhao and Wu 2017a).

Numerical simulations based on sensitivity experiments (virtual data) have also been employed for qualitative analysis in this area of research. Some studies have focused on the impacts of certain categories of land use changes, such as urbanization or deforestation and reforestation. Other studies have been conducted based on existing data taken from the literature. However, the scarcity of dynamical LULC data at regional scales for regions such as East Asia is an important obstacle in studying the East Asian monsoon (EAM). Here, satellite data from 1980 to 2010 with a spatial resolution of 30 km are used to detect the LULC changes (Li et al. 2017).

Disagreement exists between the observed data and simulated results from RCMs. The uncertainties in RCMs stem from a lack of knowledge of the relevant physical mechanisms, the parameterization schemes used, the coarse resolution of the models, and the driving fields. Meanwhile, the failure to represent land use characteristics also contributes to the difference between the observation and simulation. Current RCMs usually fail to represent the components of the general monsoon system and cannot correctly describe feedbacks between the climate and ecosystems (Fu 1997).

In general, the effects of LULC changes are geographically isolated (Pitman et al. 2012). Therefore, their impacts at global or regional scales may be low, and the importance of local scales is worthy of attention (Findell et al. 2007). These impacts will alter local energy and water cycles, thereby affecting local, regional, and global climate. Here, changes in radiation budget and SAT are explored to detect the impacts of LULC changes over East Asia and in the various subregions of China.

2. Data and experimental design

The data used to drive the WRF and experimental design are the same as those in Zhao and Wu (2017b), which are described in detail in section 1 of the Supplemental Material. In order to evaluate the local impacts of LULC, changes in SAT over subregions of China were compared (Figure S1b). The Rapid Radiative Transfer Model for GCMs (RRTMG) shortwave and longwave radiation schemes (Mlawer et al. 1997) with a flexible approach for reading the annual greenhouse gas concentrations (WRF modifications for regional climate simulation (Fita, Fernandez, and Garcia-Diez 2010) were adopted. Two numerical experiments, which shared the same integrated backgrounds, including physics processes, parameterization schemes, greenhouse gas concentrations, and driving fields (boundary and initial conditions), with the exception of the LULC data in 1980 (LU80) and 2010 (LU10) respectively (Li et al. 2017), were integrated for 36 years.

Commonly used numerical models fail to reflect the subgrid-scale variability of land use properties, because the dominant land use category within individual grid cells is used (the ‘dominant approach’ (Guo and Chen 1994)). Here, to clearly describe LULC changes at subgrid scales, a mosaic approach within the unified Noah land-surface model for land use categories developed by Li et al. (2013) was adopted instead. In the mosaic approach, a number of tiles, N (here, N = 3), were considered within particular grid cells, each of which represented a kind of land use category. Therefore, climatic variables, such as land surface temperature, albedo, and roughness length for the grid cells were calculated separately for each tile, and these quantities were then recalculated based on the relative ratio of each of the three tiles in the grid cell under consideration.

To evaluate the model’s ability in simulating SAT, the observed SATs from 2400 meteorological observation stations (resolution: 0.25° × 0.25°) across the whole of China (Wu and Gao 2013), and from version 4.01 University of Delaware data (resolution: 0.5° × 0.5°) for outside China (Matsuura and Willmott 2015), were used for comparison with the simulated results. The results showed that the model performed well (see section 3 of the Supplemental Material).

3. Results

3.1. Changes in albedo

Comparisons of the land use categories between LU80, LU10, as well as for LU01, for the three dominant tiles, using the mosaic approach, showed that the sum of mean areal land use fractions for the three dominant tiles over the terrestrial areas were 97.9%, 97.7%, and 96.3% for LU80, LU10, and LU01, respectively. The corresponding values were 92.7%, 92.2%, and 90.9% for the two dominant tiles and 75.9%, 74.0%, and 75.4% for the most dominant tile. The most dominant tiles (nearly 75%) revealed the main
changes of each of the land use categories; however, the second (nearly 17%) and third (nearly 5%) dominant tiles also expressed substantial coverage and changes, which can be further revealed by changes in albedo. The number of changed model grid cells was 7084 for LU10-minus-LU80 for the first dominant tiles across the simulated domain, which was approximately 21.7% of the total number of analyzed land grid cells. Detailed comparisons between LU80 and LU10 are discussed in section 2 of the Supplemental Material.

Changes in albedo for the three dominant tiles totaled together, and the three individual tiles between LU80 and LU10, can further reveal the importance of the mosaic approach, as shown in Figure 1. The spatial distributions of the total and the first dominant tiles were similar; however, marked differences could be detected, which indicates that the contributions to albedo changes from the second and third dominant tiles are non-negligible (the corresponding land use fractions should be considered when calculating contributions to albedo changes from the three tiles (Li et al. 2013)). These differences indicate that errors might exist in the albedo changes for model integrations performed using the dominant approach, as compared to integrations using the mosaic approach, which would further have an effect on surface energy cycles.

Our attention was concentrated on LULC changes and their impacts on the regional radiation budget, in which the dominant land use categories within grid cells might be unchanged due to the spatial resolution of the data and the intensity of LULC changes. The mosaic approach can more precisely describe the subgrid-scale land surface characteristics.

### 3.2. Influences of LULC changes on SAT

For the three subregions (subregion between 110°E and 125°E that covers East Asia (SREA); subregion to the west of 98°E (SRINDIA) that includes the Indian subcontinent; and subregion between 98°E and 110°E that includes the Indochina Peninsula (SRINDO) (Wang and Lin 2002), the annual SAT changes caused by the LULC changes were generally negative over SRINDO and SRINDIA, with the exception of the positive values noted during summer (June–July–August, JJA) at middle to high latitudes and in autumn (September–October–November, SON) at low to middle latitudes in SRINDO (Figures S3(g–i)). However, in SREA, the SAT increased at low to middle latitudes throughout the year, as well as at middle to high latitudes in summer. On the other hand, the SAT decreased in other areas, especially between 35°N and 50°N.

In terms of the spatial distributions (Figure 2), the annual results displayed negative values for the SAT changes throughout the simulated domain, with the exception of the positive values seen in the southeastern part of China, which displayed consistency between changes of albedo and impacted SAT. The areas with SAT changes that were
Marked subregional characteristics for SAT changes could be detected, and these characteristics reflected increased SAT in the southeastern part of China, whereas decreases were noted in other subregions. Meanwhile, the extent of the decreases in SAT was greater than the extent of the increases, which resulted in a decrease in China’s overall SAT (−0.062 °C). For EAL, the contributions from the LULC changes were also negative (−0.061 °C). Meanwhile, marked seasonal characteristics for SAT changes could be detected.

3.3. Influences on the radiation budget

The impacts of LULC changes on SAT arise from changes in the radiation budget at the surface and in the upper atmosphere, which plays an important role in the energy and water exchanges in the earth–atmosphere system.

3.3.1. Influences at the surface

The annual mean radiation budget changes caused by the LULC changes at the surface are shown in Table S1 and Figure 3(a). In the subregions of China, the RFs at the surface (RFB) were positive in the Northern China (NC), Eastern China (EC), Southern China (SC), Southwestern China (SW) and eastern part of Northwestern (NWE) subregions, whereas they were negative in the Northeastern China (NE), western part of Northwestern (NWW), and Tibetan Plateau (TP) subregions. The total RFBs were negative (−0.44 W m⁻²) for China as a whole and for EAL (−0.47 W m⁻²). The variations in RFB among the different subregions can be expressed in terms of the changes in the radiation budget.

Because of the urbanization that has occurred within eastern China (Zhao and Wu 2017c), the RFB there was different from that of western China, between which clear differences in the changes in the shortwave and longwave fluxes could be detected. The changes in the radiation budget differed between southeastern China and northwestern China. The shortwave components increased and the longwave components decreased for the former, while opposite changes were noted for the latter.

In southeastern China, the weakened downward (SWDB, −0.026 W m⁻²) and upward (SWUB, −2.07 W m⁻²) shortwave flux induced an increased shortwave flux (SWB, 2.04 W m⁻²); meanwhile, the intensified downward (LWDB, 0.36 W m⁻²) and upward (LWUB, 1.01 W m⁻²) longwave fluxes induced a decreased longwave flux (LWB, −0.65 W m⁻²). Therefore, the increased SWB and the decreased LWB resulted in a positive RFB (1.39 W m⁻²). However, in northwestern China, the intensified SWDB (0.26 W m⁻²) and SWUB (1.34 W m⁻²) induced a decreased SWB (−1.08 W m⁻²); meanwhile, the weakened LWDB (−0.40 W m⁻²) and LWUB (−0.98 W m⁻²) induced an increased LWB (0.58 W m⁻²). As a result, the

Figure 2. Spatial distributions of the (a) annual and (b, c) seasonal (JJA and SON, respectively) average SAT changes for LU10-minus-LU80. Hatched regions denote areas that passed the t-test with a confidence level of 90% (units: °C). Statistical significant (t-test; 90% confidence level) were primarily located to the south of 50°N. Meanwhile, the effects on SAT had marked seasonal characteristics and were less significant in spring (March–April–May; figures omitted) and winter (December–January–February; figures omitted), and much stronger in summer and autumn. The seasonal results shared similar spatial distributions as those of the annual results, with the exception of the positive values seen over Mongolia and the central and eastern parts of Russia in summer. The influenced SAT were attributed to not only changes in local energy and water cycles due to LULC changes, but also the impacted large-scale circulations, with which the weakened northward moisture flux induced decreased precipitation and increased SAT in summer over the northern part of EAM subregions (Zhao and Wu 2017b).

The subregional characteristics of the annual mean SAT changes for LU10-minus-LU80 in the subregions of China (Figure S1b) are shown in Table S1. Marked subregional characteristics for SAT changes could be detected, and these characteristics reflected increased SAT in the southeastern part of China, whereas decreases were noted in other subregions. Meanwhile, the extent of the decreases in SAT was greater than the extent of the increases, which resulted in a decrease in China’s overall SAT (−0.062 °C). For EAL, the contributions from the LULC changes were also negative (−0.061 °C). Meanwhile, marked seasonal characteristics for SAT changes could be detected.
3.3.2. Influences in the upper layer of the atmosphere

Comparisons of the annual mean RF in the upper atmosphere (RFT) and its components for LU10-minus-LU80 are shown in Table S1 and Figure 3(b). The RFTs mainly originated from changes in the upward shortwave (SWUT) and longwave (LWUT) components.

In the subregions of China, the RFTs were similar to the RFBs, which were positive in the NC, EC, SC, SW, and NWE subregions, whereas they were negative in the NE, NWW, and TP subregions. The total RFBs were negative (−0.56 W m$^{-2}$) across China as a whole and in EAL (−0.50 W m$^{-2}$). The varied RFTs noted for the different subregions could also be expressed in terms of the changes in radiation budget.

Similar to those at the surface, comparisons were performed between southeastern and western China; here decreased SWB and the increased LWB resulted in a positive RFB (−0.50 W m$^{-2}$).

For China as a whole, the RFB was negative, which resulted from the decreased SWB (which itself stemmed from the enhanced lesser SWDB and greater SWUB) and the increased LWB (which stemmed from the weakened lesser LWDB and greater SWUB). Regarding EAL, changes in the radiation budget were similar to those in China.

Therefore, greater changes could be detected for SWUB, caused mainly by changes in albedo. Meanwhile, changes in other surface radiation components (SWDB, LWDB, and LWUB) and SWUB together resulted in changes in net radiation fluxes, which had influences on sensible and latent heat fluxes, and then SAT and water vapor fluxes. As a result, SWUB and LWUB were impacted and induced changes in the radiation budgets in the upper atmosphere.

Figure 3. Changes in the (a, b) annual, (c, d) JJA, and (e, f) SON mean values for the radiation budget (a, c, e) at the surface and (b, d, f) in the upper atmosphere in subregions of China (southeastern and northwestern China), China as a whole, and East Asia, from LU10-minus-LU80 (units: W m$^{-2}$).
Table 1. Changes in the JJA mean values for climatic variables (albedo, sensible and latent heat flux (units: W m⁻²), Bowen ratio, soil moisture (units: cm² s⁻¹), upward moisture flux at the surface (units: 10⁻⁶ kg m⁻² s⁻¹), roughness length (units: m), near-surface wind speed (units: m s⁻¹), total cloud, leaf area index) over southeastern and northwestern China, China as a whole, and the land areas of East Asia (EAL), based on LU10-minus-LU80.

|                      | Southeastern China       | Northwestern China       | China            | EAL             |
|----------------------|--------------------------|--------------------------|------------------|-----------------|
| Albedo               | -0.0094                  | 0.0083                   | 0.0033           | 0.0038          |
| Sensible heat flux   | 2.09                     | -2.05                    | -0.94            | -1.13           |
| Latent heat flux     | -1.32                    | 0.53                     | 0.041            | -0.18           |
| Bowen ratio          | 0.017                    | -0.095                   | -0.012           | -0.012          |
| Soil moisture (10 cm)| 0.0017                   | 0.0071                   | 0.0019           | 0.0063          |
| Soil moisture (200 cm)| 0.00068                  | 0.0069                   | 0.0035           | 0.0066          |
| Upward moisture flux at the surface roughness length | 0.041 | -0.0017 | 0.0082 | -0.0060 |
| Near-surface wind speed | -0.071                   | -0.011                   | -0.031           | -0.0023         |
| Total cloud fraction | -0.0045                  | 0.0013                   | -0.00081         | -0.00060        |
| Leaf area index      | 0.056                    | -0.15                    | 0.0073           | -0.091          |

With the decreases in albedo, the SWUB was weakened. This effect, due to changes in albedo, was stronger than the increased SWDB and resulted in an increased SWB. The skin temperature increased, which induced increases in the sensible heat flux and LWUB. The Bowen ratio increased with decreased latent heat flux and moisture fluxes from the land surface to the atmosphere (also due to the increased roughness length, which induced weakened near-surface wind speeds). Soil moisture weakly increased, with a relative value of 0.4% for surface soil moisture at 0–10 cm. Meanwhile, the increases in sensible heat flux (2.09 W m⁻²) and the decreases in latent heat flux (−1.32 W m⁻²), which induced more heat flux release to the atmosphere and heated near-surface atmosphere, contributed to the increased SAT.

Changes in cloud fractions were similar between low- and high-cloud fraction (Table S2). Differences were detected for mid-cloud fraction, which was negative in EC but positive in SC, resulting in an increased mid-cloud fraction in southeastern China. Due to much greater convective activity over southeastern China, which induced a deep low-cloud fraction, the low-cloud fraction in these areas was greater than that for the mid- and high-cloud fractions. The decreased low-cloud fraction mainly contributed to the enhanced SWDB in southeastern China. Meanwhile, the LWDB increased, due to the intensified reflected LWUB. As a result, the more strongly positive SWB and the less negative LWB resulted in an increased RFB.

In northwestern China, the LULC changes reflected decreasing leaf area index values, sensible heat fluxes, Bowen ratio values, and roughness lengths, as well as increasing albedos, latent heat fluxes, upward moisture flux at the surface, and total cloud amounts (Table 1). With the increased albedo, the SWUB intensified, which was much stronger than the increased SWDB and resulted in a decreased SWB. The skin temperature decreased, which induced a decreased sensible heat flux and LWUB. The Bowen ratio decreased with the decreased sensible heat flux and increased latent heat flux. The moisture flux from the land surface to the atmosphere was enhanced, which was attributed to the increased soil moisture (greater than that in southeastern China), though the near-surface wind speeds decreased weakly. Meanwhile, with the decreased sensible heat flux (−2.05 W m⁻²) and the increased latent heat flux (0.53 W m⁻²), less energy was transported from the surface to heat the near-surface atmosphere, inducing the decreased SAT.

In northwestern China, due to the weaker convective activity, the low-cloud fraction was much smaller than that of mid and high cloud (Table S2). The high-cloud fraction was the largest among the three fractions, which resulted in enhanced SWDB from the decreased high-cloud fraction. Meanwhile, the LWDB weakened due to the decreased...
reflected LWUB. As a result, the more strongly negative SWB and the less positive LWB resulted in a decreased RFB.

For the subregions across the whole of China and EAL, the changes in climate variables were quite similar, with the exception of the differences seen in the changes in latent heat flux, roughness length, and leaf area index, which might be attributable to differences in climate sensitivity (Davin, Noblet-Ducoudre, and Friedlingstein 2007).

For example, the JJA RFBs over the NWE and TP subregions were 0.51 W m\(^{-2}\) and \(-5.36\) W m\(^{-2}\), respectively, whereas the corresponding SAT changes were quite similar, which were \(-0.10\) °C and \(-0.16\) °C respectively.

4. Discussion and conclusions

Using satellite-based dynamic LULC data for the years 1980 and 2010, the impacts on the radiation budget and SAT are discussed. This analysis is based on the results of numerical experiments using the mosaic approach for the model grid cells. This approach can describe the subgrid-scale land surface characteristics and detect the subgrid-scale LULC changes more precisely.

The contributions to the annual mean SAT changes were negative in EAL (\(-0.061\) °C). In the subregions of China, subregional variability in SAT changes could be detected; SAT increased in the southeastern parts of China, whereas it decreased in the other subregions. Overall, the decrease was greater than the increase, which resulted in a net decrease (\(-0.062\) °C).

The RFBs and RFTs were both negative over EAL (\(-0.47\) and \(-0.50\) W m\(^{-2}\)), and the corresponding values were \(-0.44\) W m\(^{-2}\) and \(-0.56\) W m\(^{-2}\) respectively, across China as a whole. However, marked subregional characteristics could be detected in the subregions of China for the RFBs. Changes in the radiation budget and SAT in the subregions of China can be mainly explained by the changes in albedo, latent heat flux, moisture flux, and the vertical distribution of clouds caused by the LULC changes, which can be further explained by the conversions from some land use types to others. Meanwhile, greater changes could be detected for SWUB, which mainly resulted from the changes in albedo.

Spatial changes in radiation budget were mostly consistent with those of albedo; however, differences could be detected. The impacts on radiation budget and SAT at a certain model grid resulted from not only local vertical energy and water exchanges, but also advection effects, for which the former might be much more intense and induce greater impacts at local scales than at regional scales. For example, JJA RFBs over the TP subregion were \(-5.36\) W m\(^{-2}\), while it was only \(-0.50\) W m\(^{-2}\) across the whole of China and EAL. Although the impacts of LULC changes in global terms were minor compared with other factors, and were even lower on the regional scale, the importance of the local impact and the corresponding radiation components were nonetheless significant.

LULC changes were proven to have considerable impacts on the inhomogeneity of climatic variables, which was the main purpose of the paper. However, cumulus parameterization schemes during the integrations might also have influences on the simulated values, such as the cloud fractions at different levels, for which results from ensemble simulations using different parameterization schemes (including cumulus parameterization schemes, land-surface schemes, and boundary-layer schemes) will be more objective.

Disclosure statement

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