Inclusion of land use changes in long-term regional climate simulations over East Asia

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Abstract

Long-term simulations with regional climate models (RCMs) show biases over East Asia that result partly from fix-in-time land use data (EX2001). Using four satellite-based land use images (EX8901) from the past 30 years instead of default values, 34-year integrations were performed to make comparisons (EX8901 minus EX2001) over East Asian land areas. The decreased albedo (−0.019) resulted in weakened upward short-wave flux, contributing to positive surface radiative forcing (2.89 W m⁻²), which then induced enhanced sensible heat fluxes. The near-surface wind speed was weakened (−0.15 m s⁻¹) in relation to the increased roughness length (0.042 m) and weakened pressure gradient, and induced a decreased precipitation bias of 0.0095 mm day⁻¹. The increased ground temperature and enhanced soil water content promoted strengthened sensible and latent heat fluxes, which induced a decreased surface air temperature bias (−0.24 °C). Results show that by including land use changes, model simulations can be improved.

Keywords: land use changes; albedo; roughness; surface air temperature; precipitation

1. Introduction

Although modeling with regional climate models (RCMs) is useful for regional climate studies, biases for surface air temperature (SAT) and precipitation, which also show evident subregional characteristics, are detected over East Asia (Fu et al., 2005; Zhao et al., 2009; Zhao, 2013). The East Asian region has a complex topographical distribution and is controlled by a typical monsoon climate system (Fu, 1997). Simulated SAT is generally underestimated and the rain belt is shown to be further north than it actually observed position, which then induces stronger precipitation in the north and weaker in the south over the East Asian Monsoon (EAM) regions. The biases ultimately culminate in a failure to accurately express physical mechanisms of fluid dynamics in RCMs because of difficulties with model development. Meanwhile, the adoption of different physical processes parameterization schemes due to the limitation of computation resources also make contributions. In addition, biases also result from several aspects relating to driving fields, including initial and boundary conditions from reanalysis data, as well as land use data.

Land surface changes can have significant influence on the interaction between land and atmosphere with respect to energy and water exchanges (Matthews et al., 2003; Davin et al., 2007). This occurs particularly in subregions undergoing rapid economic development and associated anthropogenic activities, such as East Asia and China. Unfortunately, although land use data in commonly used 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 (NCAR) Mesoscale Model (Grell et al., 1994) originate from satellite data, they use fixed-in-time values, and although such data can be adopted to perform seasonal and annual studies they are inadequate for use in decadal studies.

With rapid urban development and the population increase over the past few decades in East Asia, particularly in China (Fang, 2009), land use changes express obvious decadal characteristics both spatially and temporally, based on satellite-retrieved results. For example, the growth rate of built-up surfaces since the 2000s is almost double that occurring between the 1980s and 2000s, and there is evident spatial expansion from eastern to western China (Liu et al., 2014). Areas of cropland have decreased in southern China and been converted to built-up surfaces, but have increased in northeast China (from forestland) over the past 30 years. Furthermore, policies designed to return farmland to grassland and forest have had significant influences on land use changes in northern China (including northwest, northeast, and north China), particularly since the 2000s (Fan et al., 2009), and have resulted in increased forest coverage in China from 12.00% in 1981 to 21.63% in 2013 (Liu, 2014).

Many previous studies have been conducted to ascertain the influence of land use changes on regional climate, through the impact of albedo and roughness...
(Brovkin et al., 2013; Ghimire et al., 2014), but due to the lack of varied data showing land use changes, most have focused on the changes of a particular land use category. In this study, to determine the influences of using varied land use data in a regional climate simulation, four satellite-derived images for the 1980s, 1990s, 2000s, and 2010s (abbreviated as LU80, LU90, LU00, and LU10) over East Asia, instead of using default fix-in-time values, are used to perform numerical simulations in the WRF model. By using relatively ‘real’ land use data that can show land use changes over the past 30 years, dynamical downscaling method is used to address the importance in including land use changes in long-term simulations over East Asia.

2. Methods and data

2.1. Experimental design

The WRF model was used to conduct two experiments with a model integration of 34 years (1981–2014). The control run (EX2001) was conducted using default fix-in-time 20-category land use data (based on satellite images in 2001). In contrast, the experiment EX8901 used varied land use data (LU80, LU90, LU00, and LU10) for integrated years of 1981 and 1984, 1985 and 1994, 1995 and 2004, and 2005 and 2014, respectively. The integrations were comprised of a series of experiments that restarted from January 1 of 1980, 1983, 1994, 2004 for the periods 1980–1984, 1984–1994, 1994–2004, and 2004–2014, in which the first year was regarded as ‘spin-up’ time and not used in the analysis. Central latitude and longitude of the simulated domain were 35°N and 108.5°E, respectively (as shown in Figure S1, Supporting information), and the horizontal mesh consisted of 289 grid points in the longitudinal direction and 229 grid points in the latitudinal direction, including a 10-point-grid buffer zone not used in analysis. The horizontal resolution was 30 km and the time step was 60 s. Pressure at the top of the model was 10 hPa, and there were 51 levels in the vertical direction. The unified Noah land-surface model, including urban effects and emissivity in computing surface temperature (urban canopy model), was adopted in simulations. This land surface scheme could capture the feedback of land-surface forcings through a four-layer soil model, in which evapotranspiration, soil drainage, and runoff, the roughness length etc. were computed based on vegetation data and soil texture. Therefore, sensible and latent heat fluxes from land surface to the boundary layer could be objectively described and computed in the model, which could improve the mode’s ability on heat flux simulations (Chen and Dudhia, 2001). Other physical parameterization schemes included the WRF Single-Moment 6 class graupel microphysics scheme, the Community Atmosphere Model short-wave and long-wave radiation schemes, the Yonsei University boundary-layer scheme, and the Grell 3D ensemble cumulus scheme.

2.2. Data

Detailed information of methods used in obtaining satellite-retrieved data to reveal land use changes over the last 30 years were described in Wang et al. (2014); Xiao et al. (2014), expressed by Text S1. Initial conditions and time-varying boundary conditions for integrations were provided by the NCEP/NCAR reanalysis dataset with a resolution of 2.5° × 2.5°; these were bilinearly interpolated into the WRF model domain and updated every 6 h.

To evaluate the model’s performance with SAT and precipitation simulations, observed SAT data from the global terrestrial air temperature 1981–2014 monthly gridded time series (version 4.01) were adopted (Matsuura and Willmott, 2011). In addition, the Global Precipitation Climatology Centre (GPCC) Monitoring Product (1981–2014, Schneider et al., 2010), was used as the observational precipitation dataset. The observed SAT and precipitation data, both with a resolution of 0.5° × 0.5°, were then remapped to the same model grid.

3. Results

3.1. Transitions in individual land use categories

Transitions in individual land use categories using four images of EX8901 (Table 1) showed that changes for the following land use categories were relatively greater than others: forests, open shrubland, grassland, cropland, cropland/natural vegetation mosaics, and barren or sparsely vegetated land. The grid cells that showing changes in EX8901 were 6244, 6530, 6230, and 7084 from LU80 to LU90, LU90 to LU00, LU00 to LU10, and LU80 to LU10, respectively, across the whole simulated domain, which was approximately 19.8, 20.8, 19.7, and 22.5% of the total analyzed land grid cells. The land cover classes that experienced the most change per decade (or total 30 years) out of total numbers of land cover classes ranged between 4.4 and 5.7%. As the albedo and roughness length varied under different land use categories, it was considered that land use changes in nearly 11% of the total model grid cells would thus have a definite influence on regional energy and water cycles (Betts et al., 2007), thereby impacting the regional climate. In addition, land use changes were found to have an intense difference in spatial.

3.2. The impacts on SAT and precipitation

The model expressed good performance on SAT simulations in spatial over East Asia (Figure S2); however, the annual averaged SAT from EX2001 was generally underestimated across the simulated domain, as well as for subregions of China (Table 2). Underestimations were stronger in the north but weaker in the south, with the largest bias occurring in the Tibet Plateau. There were positive differences in SAT when using EX8901 compared to EX2001, with a consistently decreasing bias of 0.24 ~ 0.65 °C over the simulated domain, as

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between 98° and 110°E, including the Indo-China Peninsula.

Spatial distributions of simulated annual averaged SAT (shown in Figure 1) over East Asian land areas from EX2001 show that SATs were generally underestimated in the three subregions, which was consistent with the results shown in Table 2. The biases were stronger in spring (March–April–May, MAM) and winter (December–January–February), especially in the areas between 40 and 50°N in MAM, but were less in the summer (June–July–August, JJA) and autumn (September–October–November). Biases were decreased to a certain degree in EX8901. Even though the land cover changes improved the bias, a negative bias still existed. However, biases were slightly enhanced during JJA in both SRI and SRIII.

Spatial distributions of simulated results for precipitation over East Asian land areas from EX2001 are shown in Figure 2. In the EAM subregion (SRI), precipitation was underestimated in the south and overestimated in the north with EX2001, but with EX8901 the biases in the south were reduced to a certain degree. For the other two subregions (SRII and SRIII), precipitation was generally overestimated in the south but underestimated in the north with EX2001, but any large biases were decreased using EX8901 to a certain degree.

3.3. The influence on regional energy and water cycle

Influences on the regional energy cycle (Table 3) from EX2001 to EX8901 reflected a positive radiative forcing at surface (RFB) of 2.89 W m⁻², resulting from an enhanced net short-wave flux (SWB, 2.92 W m⁻²) and a weakened net long-wave flux (LWB, −0.034 W m⁻²). The ground surface was heated with an intensified RFB, which contributed to enhancing the sensible (1.55 W m⁻²) heat flux and upward long-wave flux (LWUPB, 1.33 W m⁻²). The increased ground temperature, and soil water content (0–2 m) due to the intensified precipitation contributed to the enhanced latent heat flux (1.31 W m⁻²), which promoted a greater amount of moisture flux into the atmosphere. The strengthened sensible and latent heat fluxes then resulted in increased
Figure 1. Latitude-monthly cross sections of annual variations for SAT (a, b, c) biases from EX2001 over (a, d) SRI, (b, e) SRII, and (c, f) SRIII, and the corresponding (d, e, f) differences between EX2001 and EX8901 (EX8901 minus EX2001, units: \(\circ\)C).

Figure 2. Same as Figure 1, but for precipitation (units: mm day\(^{-1}\)).

SAT (0.24\(^\circ\)C). The strengthened moisture flux further induced an increased amount of cloud, which then contributed to the weakened downward short-wave flux (SWDNB) (−1.41 W m\(^{-2}\)) and strengthened downward long-wave flux (LWDNB) (1.30 W m\(^{-2}\)). In addition, the decreased albedo (−0.019) induced a strong weakened upward short-wave flux (SWUPB, −4.33 W m\(^{-2}\)), with which the decreased SWDNB induced an intense positive SWB; and the enhanced LWDNB (less) and LWUPB (greater) resulted in a small LWB. Therefore, changes in the radiation budget mainly resulted from a decreased albedo induced weakened SWUPB. The radiation budget changes at the surface further impacted the values at the top of the atmosphere, in which the radiative forcing at the top (RFT) was positive (2.48 W m\(^{-2}\)), resulting from the weakened upward short-wave flux (SWUPT, −2.85 W m\(^{-2}\)) and strengthened upward long-wave flux (LWUPT, 0.37 W m\(^{-2}\)) at the top, which were consistent with changes in SWUPB (weakened) and LWUPB (enhanced).
Land use changes in long-term climate simulations

Table 3. Changes in variables over East Asian land areas in the transition from using EX2001 to EX8901 for 34-year simulations.

| Variables                     | Changes          | Variables                     | Changes          |
|-------------------------------|------------------|-------------------------------|------------------|
| SAT                           | 0.24°C           | SWDNB                         | −1.41 W m⁻²      |
| Precipitation                 | 0.0095 mm day⁻¹  | SWUPB                         | −4.33 W m⁻²      |
| Soil moisture at 0–2 m        | 0.0021 m³ m⁻³    | LWDNB                         | 1.30 W m⁻²       |
| Albedo                        | −0.019           | LWUPB                         | 1.33 W m⁻²       |
| Leaf area index               | 0.17             | RFB                            | 2.89 W m⁻²       |
| Cloud amount (high)           | 0.0015           | SWUFT                          | −2.85 W m⁻²      |
| Cloud amount (middle)         | 0.0030           | LWUFT                          | 0.37 W m⁻³       |
| Cloud amount (low)            | 0.0028           | RFT                            | 2.48 W m⁻³       |
| Cloud amount (mean)           | 0.0024           | Sensible heat flux             | 1.55 W m⁻²       |
| Roughness length              | 0.042 m          | Latent heat flux               | 1.31 W m⁻²       |
| Near-surface wind speed       | −0.15 m s⁻¹      | SAT minimum/maximum           | 0.23/0.25°C      |

The impact on the regional water cycle from EX2001 to EX8901 shows that the increased roughness length (0.042 m) and changed pressure gradient (as shown in Figure S3 and Text S2) contributed to a weakened near-surface wind speed (−0.15 m s⁻¹), which induced a weakened EAM circulation (Wu et al., 2016b, 2016a) and the corresponding moisture flux. Over the EAM subregion, the EAM-related precipitation was concentrated in JJA and the weakened EASM due to the increased roughness length and weakened pressure gradient prevented the northward moisture flux; therefore precipitation was weakened in the north but strengthened in the south. The increased precipitation intensity in the south resulted in a decreased precipitation bias of 0.0095 mm day⁻¹. With intensified precipitation, the soil water content was then increased (0.021 m³ m⁻³). The leaf area index increased by 0.17, which contributed to the enhanced evaporation. Furthermore, the evaporation-related latent heat flux and moisture flux into the atmosphere were intensified, which further promoted an increased amount of cloud, as well as an increased SAT. Further analysis of SAT changes shows that the decreased bias resulted from an increase in minimum and maximum SAT (0.23 and 0.25°C, respectively).

3.4. Comparisons between LU00/LU10 and LU01

Further analysis of the simulated results from EX2001 to EX8901 (as shown in Table S1 and Text S3) there were small differences between the values for LU00 and LU10, thereby showing that LU00 and LU10 data were close to that of LU01.

4. Summary

The transition from using default fix-in-time land use data to that of satellite-based four images, showed that land use changes over East Asia had a direct influence on albedo and roughness length, which thus impacted regional energy and water cycles and further influenced values of SAT and precipitation in simulations.

Simulated SAT showed a consistent cold bias in EX2001; however, the biases were decreased to a certain degree with EX8901. With the changes in land use from EX2001 to EX8901, there was a decrease in the albedo (−0.019), which induced a weakened SWUPB and further contributed to a positive SWB (with a weakened SWDNB). In addition, the enhanced LWDNB and LWUPB resulted in a negative LWB. As a result, the RFB was positive (2.89 W m⁻²), which increased ground temperature and allowed for a greater amount of sensible heat flux. Over the EAM subregion, the simulated precipitation in EX2001 was weak compared to observations, which mainly resulted from the simulated intensified EAM circulation induced northward movement of a rain belt. The differences between EX2001 and EX8901 showed that the simulated EAM circulation in EX8901 was weakened due to the increased roughness length (−0.15 m s⁻¹) and weakened pressure gradient, which resulted in greater precipitation in the southeastern China coastal areas. As a result, the intense negative precipitation bias was decreased by 0.0095 mm day⁻¹, which contributed to the increased soil moisture content, as well as the evaporation and latent heat flux due to the higher ground temperature. Meanwhile, SAT bias was decreased by 0.24°C. The enhanced energy and moisture flux transferred into the atmosphere also contributed to the cloud amount, which then resulted in decreased SWDNB and increased LWDNB. The increased ground temperature also contributed to the enhanced LWUPB, and further to the strengthened LWDNB. The weakened SWUPB due to increased albedo during transitions from default fix-in-time land use to the satellite-retrieved four images accounted for major changes in the radiation budget.

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Supporting information

The following supporting information is available:

Figure S1. (a) Model domain and terrain distribution (unit: m) and (b) the eight subregions of China (NE, Northeast China; NC, North China; EC, East China; SC, South China; NWE, eastern part of Northwest China; SW, Southwest China; NWW, western part of Northwest China; TP, the Tibetan Plateau).

Figure S2. Spatial distributions for surface air temperature between observed data (a: UDEL) and simulated results (b: E2001; c: EX8901) between 1981 and 2014 (units: °C).

Figure S3. Changes of sea-level pressure in summer (June–July–August) between EX2001 and EX8901 (EX8901 minus EX2001, units: hPa).

Table S1. Changes in albedo, roughness length, SAT, SWDNB, SWUPB, RFB, and RFT with different land use data (LU80, LU90, LU100, and LU110 for integrated years 1981–1984, 1985–1994, 1995–2004, and 2005–2014, respectively), compared with the results from EX2001.

Text S1. Satellite-based land use data.

Text S2. Changes in sea-level pressure between EX2001 and EX8901.

Text S3. Differences in relation to differing land use data.

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