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Substantial impacts of landscape changes on summer climate with major regional differences: The case of China

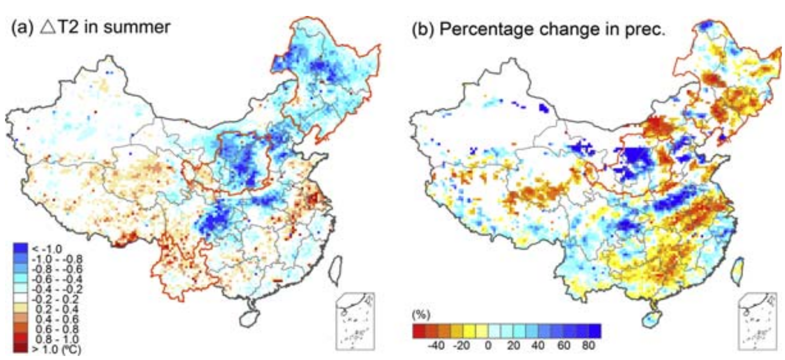
Qian Cao [a], Deyong Yu [a,*], Matei Georgescu [b], Jianguo Wu [a,c,**]

[a] Center for Human-Environment System Sustainability (CHESS), State Key Laboratory of Earth Surface Processes and Resource Ecology (ESPRE), Faculty of Geographical Science, Beijing Normal University, Beijing 100875, China
[b] School of Geographical Sciences and Urban Planning, Urban Climate Research Center, Arizona State University, Tempe, AZ 85287, United States
[c] School of Life Sciences and School of Sustainability, Arizona State University, Tempe, AZ 85287, United States

HIGHLIGHTS

- Numerical simulations with incorporation of satellite-derived landscape patterns.
- Large-scale impacts of land cover and land management change on summer climate.
- Heterogeneous climatic effects in space with identified hotspots.

GRAPHICAL ABSTRACT



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ABSTRACT

China's rapid socioeconomic development during the past few decades has resulted in large-scale landscape changes across the country. However, the impacts of these land surface modifications on climate are yet to be adequately understood. Using a coupled process-based land-atmospheric model, therefore, we quantified the climatic effects of land cover and land management changes over mainland China from 2001 to 2010, via incorporation of real-time and high-quality satellite-derived landscape representation (i.e., vegetation fraction, leaf area index, and albedo) into numerical modeling. Our results show that differences in landscape patterns due to changes in land cover and land management have exerted a strong influence on summer climate in China. During 2001 and 2010, extensive cooling of up to 1.5 °C was found in the Loess Plateau and 1.0 °C in northeastern China. In contrast, regional-scale warming was detected in the Tibetan Plateau (0.3 °C), Yunnan province (0.4 °C), and rapidly expanding urban centers across China (as high as 2 °C). Summer precipitation decreased in the northeastern region, with patchy reduction generally <1.8 mm/day, but increased in the Loess Plateau, with local spikes up to 2.4 mm/day. Our study highlights that human alterations of landscapes have had substantial impacts on summer climate over the entire mainland China, but these impacts varied greatly on the regional scale, including changes in opposite directions. Therefore, effective national-level policies and regional land management strategies for climate change mitigation and adaptation should take explicit account of the spatial heterogeneity of landscape-climate interactions.

* Correspondence to: D. Yu, No.19 XinJieKouWai Street, Beijing 100875, China.
** Correspondence to: J. Wu, P.O. Box 874501, Tempe, AZ 85287-4501, United States.
E-mail addresses: ydy@bnu.edu.cn (D. Yu), Jingle.Wu@asu.edu (J. Wu).

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1. Introduction

Land use and land cover change have been a major driver of climate change at regional and global scales (Feddema et al., 2005; Foley et al., 2005; Kabat, 2004; Marland et al., 2003; NRC, 2005; Vitousek et al., 1997) because it affects the climate system through two general pathways: biogeochemical and biogeophysical (Feddema et al., 2005). Prior studies have demonstrated that biogeophysical effects resulting from modification of land surface properties can lead to regional climate change that is on the same order of magnitude as impacts owing to biogeochemical effects due to greenhouse gas emissions (Betts et al., 2007; Georgescu et al., 2013; Pielke and Avissar, 1990). This is because alterations to land surface biophysical properties modify surface energy budget and land-atmospheric transport of heat, moisture, and momentum, with additional consequences for temperature, air circulation, and precipitation change (Pielke et al., 2011, 2016). Therefore, accurately quantifying anthropogenic influence on climate requires consideration of biogeophysical processes (Davin et al., 2007; Mahmood et al., 2014, 2016; de Noblet-Ducoudré et al., 2012), particularly for regions experiencing dramatic land surface modification.

China has witnessed unprecedented socioeconomic transformations in recent decades and intensified human activities (e.g., urbanization, agricultural intensification, and reforestation) have dramatically modified ecosystems and landscapes across the nation (Liu et al., 2014). This has been especially evident since 2000, when urbanization entered a phase of rapid development (Wu et al., 2014) and implementation of the Grain to Green Program became prevalent nationwide (Feng et al., 2016; Gao et al., 2016). Increased utility of numerical modeling approaches to estimate climate effects of landscape changes for China as a whole improved our understanding of land-atmosphere interactions in this rapidly changing part of the planet (Fu, 2003; Hu et al., 2015; Wang et al., 2013; Wang et al., 2015; Xu et al., 2015). These studies focused mainly on comparing effects of potential natural vegetation with those of current land surface conditions. In contrast, few studies have examined the possible effects of historical landscape changes on regional climate in China. This was partly because climate effects spanning a time period of several decades may not be easily detected when only including changes in land cover classes.

However, land management change (LMC, e.g., the influence of different grazing intensities on grassland characteristics) can have similar or greater effects on land surface biophysical properties and therefore regional climate than land cover change (LCC, e.g., the conversion from forests to croplands). It is important to recognize that LMC may be independent of LCC. To date, limited research exists examining climate impacts of LMC that occurs within the same land cover type and does not result in LCC (Luyssaert et al., 2014). Although the representation of LMC has been restricted by inadequate data availability and excessive computing demands, omission of this subgrid-scale landscape heterogeneity will result in underestimation of climate effects and reduced skill of model performance (Cao et al., 2015; Georgescu et al., 2009; Pielke and Avissar, 1990; Weaver and Avissar, 2001). Fortunately, recent advances in remote sensing techniques and computational capacity facilitate the usage of real-time and high-quality data to characterize landscape changes induced by LCC and LMC.

Here we apply the Weather Research and Forecasting (WRF) Model (Skamarock and Klemp, 2008) to quantify impacts of landscape changes on summer climate over China. Our study focuses on summer season (we define summer as June, July, and August) because vegetation matures to peak greenness and thus exerts the strongest influence on land-atmosphere interactions during this period of time. We parameterized WRF on a 30-km basis using satellite-derived landscape patterns corresponding to 2001 and 2010, which differed in the representation of land cover and land surface biophysical properties (i.e., vegetation fraction, leaf area index, and surface albedo). We seek to answer the following questions: 1) Did land cover change or land management change result in greater landscape changes in China during 2001–2010? 2) Did these landscape changes have any major effects on regional climate across the country? 3) How did the climate effects of landscape changes vary spatially from region to region?

2. Materials and methods

2.1. Model configuration and parameterization

Simulations were performed using the Weather Research and Forecasting (WRF) model with the advanced dynamical core. The WRF model was configured with a one-way domain having grid spacing of 30 km in both horizontal directions (Fig. 1). The domain was centered on 36.5°N and 103°E with 200 grid cells along east-west direction and 170 grid cells along north-south direction, encompassing the entirety of China and portions of the Indian and Pacific Oceans, with a total area of 6000×5100 km^2. This domain configuration was deemed sufficiently expansive to capture the influence of the East Asian Monsoon on summer climate in China (Hu et al., 2015). A Lambert conformal conic projection was used for the model's horizontal coordinate while the model's vertical coordinate employed 30 terrain-following eta levels from the surface to 50 hPa. The initial and lateral boundary conditions for large-scale atmospheric fields were obtained from the Global Final Analysis (FNL) data archive, maintained by the National Centers for Environmental Prediction (NCEP; http://rda.ucar.edu/), with a 6-h temporal frequency and 1° grid spacing in both horizontal directions.

The main physical parameterizations used for all simulations are presented in Table 1. In order to represent land surface processes, the community Noah land surface model (LSM; Chen and Dudhia, 2001; Ek et al., 2003) coupled with the WRF model was utilized to simulate the energy and momentum exchange between the land surface and overlying atmosphere. However, although the coupled Noah LSM has been widely used to facilitate regional climate modeling, deficiencies exist with its prescribed land surface biophysical properties (Cao et al., 2015). In this work, therefore, we employed recently developed satellite-estimated landscape data with more detailed biogeographic information to improve characterization of landscape in the Noah LSM, and above all, to represent modification of biophysical properties arising from land management change.

2.2. Remotely sensed data acquisition

We obtained land cover data from the Data Center for Resources and Environmental Sciences, constructed by the Chinese Academy of Sciences (http://www.resdc.cn). The land cover data for 2000 and 2010 were derived from Landsat TM imagery with a spatial resolution of 1 km × 1 km. The data were classified according to the International

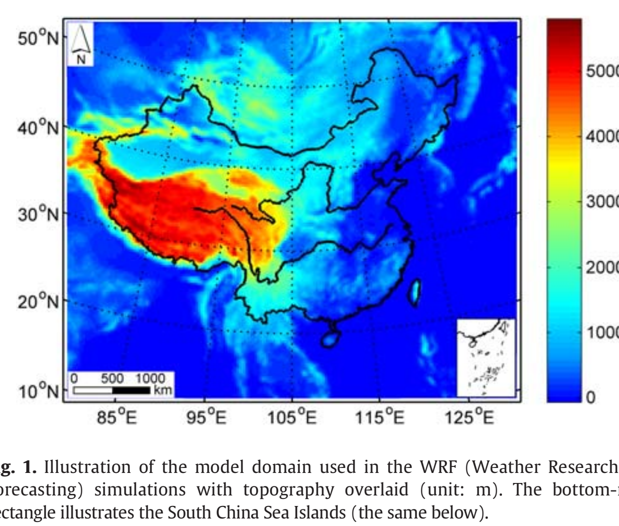

Fig. 1. Illustration of the model domain used in the WRF (Weather Research and Forecasting) simulations with topography overlaid (unit: m). The bottom-right rectangle illustrates the South China Sea Islands (the same below).