RESEARCH ARTICLE
10.1002/2014JD022288

Key Points:
- The impact of LUCCs on climate is simulated using a regional climate model
- LUCCs may result in a weaker summer monsoon over eastern China
- LUCCs may produce an anomalous cyclonic circulation over northeastern Asia

Citation:

Received 5 JUL 2014
Accepted 10 DEC 2014
Accepted article online 13 DEC 2014

Abstract Eastern China has experienced substantial agricultural expansion and deforestation in recent decades. We modeled the influence of land use/cover changes (LUCCs) over eastern China on the regional climate using the Weather Research and Forecasting model with the Noah-multiparameterization land surface scheme. Two 21 year (1980–2000) experiments were performed using the same settings, except for the land use/cover data for the 1980s and the 2000s. The results showed that in northern China, decreases in the surface air temperature of approximately 0.3–0.5°C and decreases (increases) in rainfall over the lower reaches of the Yangtze River valley (southern China, northeastern China, and the Korean Peninsula) of approximately 3% (6–7%) in the summer were associated with LUCCs in eastern China from the 1980s to the 2000s. The cooling effect in northern China, which was primarily attributable to an increase in the surface latent heat flux of approximately 7.3–9.6 W m$^{-2}$, weakened the land-ocean thermal contrast, suggesting the presence of a weaker summer monsoon over eastern China. As a result, rainfall over the lower reaches of the Yangtze River valley (southern China) tended to decrease (increase). In addition, the cooling effect may have produced an anomalous cyclonic circulation from the surface to the midtroposphere over northeastern China and the Korean Peninsula, resulting in increased rainfall over this area.

1. Introduction
Humans affect climate through greenhouse gas (GHG) emissions and land use/cover changes (LUCCs) [e.g., Dimeyev et al., 2010; Mahmood et al., 2013]. The regional cooling effect resulting from deforestation and agriculture at midlatitudes has been reported to be of a similar magnitude to the GHG warming [Bettis et al., 2007; Diffenbaugh, 2009]. As the bottom boundary of the atmosphere, LUCCs regulate local/regional weather and climate by directly modifying the surface radiation budget and exchanges of heat, water, and momentum [Notaro et al., 2006]. Knowledge of how LUCCs affect local/regional weather and climate would be valuable for assessing anthropogenic impacts on climate change [e.g., Anav et al., 2010; Mahmood et al., 2010; Pitman et al., 2012].

Significant population increases and socioeconomic activities have intensified LUCCs over China. Many studies have examined the climate impacts of LUCCs over China and East Asia using observational data and numerical simulations [Fu, 2003; Gao et al., 2003, 2007; Sen et al., 2004; Ding et al., 2005; Li and Xue, 2010; Zhang et al., 2010; Jiang and Liang, 2013; Zhang et al., 2014]. For example, based on observations, it was found that the improved vegetation greenness over northwestern China increased (decreased) the local atmospheric water vapor (precipitation) amount in summer (spring) [Jiang and Liang, 2013; Zhang et al., 2014]. However, land-atmosphere interactions are highly nonlinear, especially in East Asia, which exhibits a distinctive monsoon climate. Therefore, numerical simulations using different land cover maps based on a general circulation model (GCM) or a regional climate model (RCM) coupled with a land surface model are useful for quantitatively determining the climate impacts of LUCCs over China. Based on a GCM, Li and Xue [2010] compared simulations using satellite-derived land cover maps and potential vegetation maps over the Tibetan Plateau (TP), concluding that land degradation of grassland to desert led to a weaker monsoon circulation and decreased precipitation on the southeastern TP. In comparison to GCMs, high-resolution RCMs have been widely used to detect the effects of LUCCs on East Asian climate because such models are...
more capable of describing surface heterogeneity and topography, which may be important for the LUCCs studies [Gao et al., 2003]. With the use of the RCM, many studies have conducted simulations using current land use and potential vegetation cover to study the influence of human-induced LUCCs on the climate over China [Fu, 2003; Gao et al., 2003, 2007]. These studies found that anthropogenic activities, such as deforestation and farming, changed the surface albedo, evapotranspiration, and surface roughness, which may have a compounded effect on the temperature, rainfall, and circulation over China. Meanwhile, some studies have investigated the effect of idealized vegetation restoration by replacing desert and semidesert areas with grass or forest in northwestern China based on a RCM [Sen et al., 2004; Ding et al., 2005]. These works concluded that vegetation restoration could cool the surface and increase the local precipitation in summer, which may even influence the rainfall in downstream areas through circulation changes.

Although most studies have suggested that LUCCs over China may affect the air temperature, rainfall, and monsoon circulation, the LUCCs used in most previous studies are not realistic for China over the past three decades; therefore, the results cannot capture the true effect of LUCCs on regional climate during the past three decades. LUCCs from the 1980s to the 2000s can be characterized by the expansion of arable land and decreases in woodland and grassland areas. In northeastern China, large woodland and grassland were converted into farmland, while dry land decreased and paddy field increased over the Northeast China Plain. Moreover, the North China Plain and the Loess Plateau exhibited large-scale conversions from grassland to arable land. Southwestern China and hilly regions in southeastern China were dominated by land conversion from woodland to arable land [Liu et al., 2003a, 2003b, 2014]. Furthermore, during the past decade (i.e., from the 2000s to the 2010s), the primary area of arable land reclamation shifted from northeastern China and northern China to the oases area of northwestern China, while woodland areas increased on the Loess Plateau and a few southern areas [Liu et al., 2014]. In previous studies, the differences between the current and potential vegetation cover represent possible LUCCs over thousands of years, which differ from realistic LUCCs that have occurred over the past few decades. Moreover, the idealized vegetation cover changes also differ from the main vegetation cover changes over China during recent decades. Thus, to assess the influence of LUCCs in eastern China during recent decades on the regional climate, it is essential to use realistic LUCCs data in model simulations. In this study, based on satellite-measured land use/cover data from the 1980s and the 2000s and the Weather Research and Forecasting (WRF version 3.4.1) model, two long-term continuous numerical simulations spanning from 1980 to 2000 were used to explore the climate response to realistic LUCCs over eastern China during recent decades. The possible mechanisms of how LUCCs affect the summer climate were analyzed. The structure of this paper is organized as follows: the model description, experimental design, data, and analytical methods are presented in section 2; the simulation results and possible relationships between LUCCs and regional climate are presented in section 3. Lastly, the conclusions are summarized, and associated uncertainties are discussed in section 4.

2. Data and Methods

2.1. Model Description

The Weather Research and Forecasting model with the Advanced Research WRF dynamics solver [Skamarock et al., 2008] was used in this study. WRF is a flexible, state-of-the-art, fully compressible, nonhydrostatic mesoscale model that has been widely used in applications ranging from regional climate modeling [e.g., Leung and Qian, 2009] to land-atmosphere interactions [e.g., Zhang et al., 2011, 2013; Ge et al., 2014]. An application of WRF by Yu et al. [2011] demonstrated the importance of higher model resolution in reproducing precipitation well at region scale, which was further confirmed by Gao et al. [2001, 2006]. The physical parameterizations used in the WRF model include the Community Atmospheric Model radiative transfer scheme [Collins et al., 2004], the Grell-Devenyi ensemble convective parameterization scheme [Grell and Dévényi, 2002], the Yonsei University counter-gradient boundary layer turbulence transfer scheme [Hong et al., 2006], and the WRF-Single Moment three-class simple ice scheme [Hong et al., 2004].

The Noah land surface model with multiparameterization options (Noah-MP LSM), which is an augmented version of Noah LSM, was used in this study to simulate the surface state and surface flux to the atmosphere. Among the multiparameterization options, the dynamic vegetation scheme was turned off because we intended to focus on the effect of land cover on the atmosphere. A modified two-stream radiation transfer scheme was used to compute separately the energy balance over the vegetation canopy and ground surface.
Moreover, the Ball-Berry option was chosen for stomatal resistance, which considers sunlit and shaded leaves [Ball et al., 1987; Collatz et al., 1991, 1992; Sellers et al., 1996; Bonan, 1996]. The soil moisture factor for stomatal resistance was set to the default Noah option in which the factor is parameterized as a function of the soil moisture. The TOPMODEL-based runoff scheme with simple groundwater was used for modeling runoff and groundwater [Niu et al., 2007]. By considering land surface heterogeneity and 3-D vegetation structure, the Noah-MP LSM has been shown to produce more realistic surface fluxes, soil moisture, and temperature [Yang et al., 2011; Niu et al., 2011]. Moreover, Hu et al. [2014] showed that the Noah-MP LSM coupled with WRF exhibited better performance in simulating precipitation in China. In the Noah-MP LSM, the most critical parameter is the vegetation type. Other key parameters regarding the phenology (e.g., leaf/stem area index), structure (e.g., crown radius and depth), and the optical and physiological properties (e.g., leaf reflectance/transmittance) are defined in a lookup table according to the vegetation type. Several variables (e.g., the albedo and surface heat flux) that regulate the surface energy and hydrologic cycles are calculated based on these parameters.

2.2. Experimental Design

In this study, two 21 year continuous simulations (EXP 1 and EXP 2) were performed using identical settings except for using the underlying land use/cover data for the 1980s and the 2000s, respectively. The simulation domain covered the entire area of China with a central point at 37°N and 106°E. The horizontal resolution was 30 km (225 grid points in the east-west direction and 168 grid points in the north-south direction); 28 vertical atmospheric levels extended to 50 hPa were used (Figure 1). This model domain, which is selected as a typical application for the East China Monsoon simulation, accounts for the representativeness of the driving fields of the lateral boundary, the location of the buffer zone, and the inclusion of important circulation systems over eastern China [Liu, 2006]. The integration time spanned 0000 UTC on 1 January 1980 to 1800 UTC on 31 December 2000. The first year of each simulation was considered to be a spin-up period to reduce the influence of the initialization.

2.3. Data

Three types of data were used in this study. (1) Land use/cover data for the 1980s and the 2000s were used. (2) The simulations were driven by the National Centers for Environmental Prediction-Department of Energy (NCEP-DOE) Reanalysis II product [Kanamitsu et al., 2002]. (3) The gridded monthly mean temperature/precipitation data set was used for model validation, while the NCEP-DOE Reanalysis II and the ERA-Interim Reanalysis [Dee et al., 2011] data sets were utilized for regression analysis. The land use/cover grid data used in EXP 1 and EXP 2 were primarily based on the Landsat thematic mapper (TM) digital images in the 1980s and 1999/2000, respectively; China-Brazil Earth Resources Satellite-1 data were used to supplement the land use information for 1999/2000. The images were geometrically corrected and georeferenced, and the outdoor survey and random sample check testified that the average accuracy for the land use changes interpretation exceeded 95% [Liu et al., 2003a, 2003b, 2014]. Therefore, it was concluded that the difference between EXP 1 and EXP 2 could be used to illustrate the essential land use/cover conversions in eastern China from the 1980s to the 2000s. Because the satellite-derived data had a 1 km resolution and land use categories were defined by Liu et al. [2003a], we upscaled the resolution of this data set from 1 km to 30 km and performed type conversions for the land cover following the U.S. Geological Survey (USGS) land cover categories to implement the land use data into the WRF simulation. We upscaled the land use data by calculating the dominant land cover type in each WRF grid cell and...
converted the land cover type based on the rules defined in Table A1. The land cover changes between EXP 1 and EXP 2 in the frame of the WRF model are illustrated in Figure 2. The areas that were subjected to changes in land cover accounted for 15.1%, 12.8%, and 12.1% of the total areas of northeastern China (40°–49°N, 119°–126°E), northern China (33°–42°N, 105°–116°E), and southern China (23°–32°N, 104°–117°E), respectively. In northeastern China, land cover conversions were predominantly reflected by changes from savanna and grassland to cropland. In northern China, the land cover changed primarily from grassland to cropland. Moreover, in the southern area, the predominant land cover conversion was from woodland to cropland. Some of the parameters for the main vegetation types that changed between EXP 1 and EXP 2 are shown in Figure 3.

The NCEP-DOE Reanalysis II product with a 2.5 by 2.5° resolution and 6 h intervals was used for the initial and lateral boundary conditions in both simulations. In addition, this data set was used to update the sea surface temperature. Gridded monthly mean temperature [Xu et al., 2009] and monthly precipitation [Xie et al., 2007] data sets were used for model validation. The gridded data were produced using surface meteorological station data with a topographic adjustment. In the validation stage of this study, the simulated temperature and precipitation with a 30 km resolution from EXP 1 were aggregated into 0.5 by 0.5° grid cells via area weighting. In addition, the ERA-Interim Reanalysis data, including the surface air temperature, air temperature at 850 hPa, wind vectors, and geopotential height, were used in a regression analysis to potentially increase confidence in the effects of LUCCs on circulation.

2.4. Methods

Summer (June to August, JJA) climate data were analyzed. The mean differences in the variables between EXP 1 and EXP 2 (i.e., EXP 2 minus EXP 1), which are theoretically related to LUCCs, were calculated.

It is known that the East Asian summer monsoon plays a crucial role in modulating the East Asian climate, including the temperature, precipitation, and atmospheric circulation. Thus, compared with the effects of LUCCs on the climate over China, variations in the East Asian summer monsoon may conceal potential LUCCs signals in our results. To highlight the effects of LUCCs, simulation results from normal monsoon years were
analyzed, i.e., where the East Asian summer monsoon was neither strong nor weak. The strength of the East Asian summer monsoon was measured based on multiple monsoon indices, including the Western North Pacific-East Asian monsoon (WNP-EAM) index \cite{Wang1999}, the Regional Monsoon (RM2) index \cite{Lau2000}, and the East Asian summer monsoon (EASM) index \cite{Li2005}. A summer was considered to be a normal monsoon summer if the absolute value of the normalized index was less than 1 \(\sigma\) for all three indices. Several normal monsoon years, i.e., 1987, 1989, 1991, 1992, 1997, 1999, and 2000 (shown in Figure 4), were identified based on the three indices over the period from 1981 to 2000. We calculated the mean changes in precipitation, temperature, surface energy terms, and circulation between EXP 1 and EXP 2 for these seven normal monsoon years. The statistical significance of the mean changes in temperature, precipitation, and circulation were tested using the paired sample test.

3. Results
3.1. Evaluation of the Control Run
We examined the model's capability of capturing the main spatial distribution of the surface air temperature and precipitation in summer. Figure 5

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure3}
\caption{The leaf area index (LAI), stem area index (SAI), vegetation crown radius (RC; units: m), vegetation crown depth (HD; units: m), leaf reflectance for near infrared (RHOL), and leaf maintenance respiration at 25°C (RMF; units: \(\mu\)mol m\(^{-2}\) s\(^{-1}\)) for the main vegetation type that changed in EXP 1 and EXP 2 over northeastern China (NE; savanna to dry land cropland/pasture), northern China (N; grassland to cropland/grassland), and southern China (S; evergreen broadleaf forest to cropland/woodland).}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure4}
\end{figure}
presents the surface air temperature (SAT) and precipitation distributions for both observations and the control run (i.e., results in EXP 1 for 1981–1990). The spatial correlation coefficients between the observational data and the simulation results were also calculated. The control simulation reproduced the surface air temperature distribution with a spatial correlation coefficient of 0.97 ($p < 0.01$). In addition, the simulated summer precipitation in the control run agreed well with the observational data; the spatial correlation coefficient was 0.75 ($p < 0.01$). The observations and simulation results revealed three main summer rain belts located in northeastern China (40°–49°N, 120°–126°E), Central China (30°N, 100°–120°E), and southeastern China (21°–25°N, 100°–119°E). However, some biases remained (figure not shown). The simulated precipitation was higher (lower) along the edges of the Tibetan Plateau, the Khingan Range, and the Changbai Mountains.

**Figure 5.** Spatial patterns of the (top row) surface air temperature (units: °C) and (bottom row) rainfall (units: mm) based on (left column) observations and the (right column) control simulation. $R$ denotes the spatial correlation coefficient between the observations and simulation results.

**Figure 6.** Spatial patterns of the changes (EXP2-EXP1) in (a) the surface air temperature (SAT; units: °C) and (b) rainfall (units: mm) in summer (JJA) during normal monsoon years. Dotted areas are significant at the 95% confidence level.
The good model performance provides reliable skill in simulating the summer climate over China, which provides confidence for simulating how LUCCs affect the East Asian climate.

### 3.2. Simulated Temperature and Rainfall Changes

The mean differences between the EXP 1 and EXP 2 simulations (i.e., EXP 2 minus EXP 1) during normal monsoon summers (i.e., summers in 1987, 1989, 1991, 1992, 1997, 1999, and 2000) were analyzed to understand the possible effects of LUCCs on the surface air temperature and rainfall over China (Figure 6). In general, the LUCCs in EXP 2 caused a cooling effect over eastern China. An extensive cooling effect was found in northeastern (40°–49°N, 119°–126°E) and northern China (33°–42°N, 105°–116°E), while a slight decrease in the surface air temperature was simulated in southern China (23°–32°N, 104°–117°E) compared with EXP 1. The mean cooling in these regions (for all grid cells with land cover changes) was approximately −0.5°C in the northeastern area, −0.3°C in the northern area, and −0.1°C in the southern area (Table 1).

#### Table 1. Mean Changes in the Surface Energy Budget

<table>
<thead>
<tr>
<th>Region</th>
<th>Albedo</th>
<th>Net Solar</th>
<th>Latent Heat</th>
<th>Sensible Heat</th>
<th>SAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>NE</td>
<td>0.03</td>
<td>−4.5</td>
<td>9.6</td>
<td>−12.0</td>
<td>−0.5</td>
</tr>
<tr>
<td>N</td>
<td>0.01</td>
<td>−1.4</td>
<td>7.3</td>
<td>−6.6</td>
<td>−0.3</td>
</tr>
<tr>
<td>S</td>
<td>0.07</td>
<td>−13.0</td>
<td>4.1</td>
<td>−17.2</td>
<td>−0.1</td>
</tr>
</tbody>
</table>

The surface energy terms are represented by the surface albedo, net solar radiation, surface latent and sensible heat fluxes, and the surface air temperature (SAT) in summer (JJA) over grid cells with land cover changes in northeastern China (NE; 40°–49°N, 119°–126°E), northern China (N; 33°–42°N, 105°–116°E), and southern China (S; 23°–32°N, 104°–117°E). The radiation and heat fluxes were measured in W m⁻², while the surface air temperatures were measured in °C.

Figure 7. Spatial patterns of the changes (EXP2-EXP1) in (a) the surface albedo (units:10⁻²), (b) the net solar radiation at the surface, (c) the surface latent heat flux, and (d) the surface sensible heat flux (units: W m⁻²) in summer (JJA) during normal monsoon years.
The changes in summer rainfall during JJA that were associated with the LUCCs during the recent decades are illustrated in Figure 6b. The rainfall simulated in EXP 2 decreased significantly over the lower reaches of the Yangtze River valley (28–33°N, 110–122°E) compared with EXP 1, with a mean reduction of approximately 14 mm (~3% of the climatological mean in EXP 1). However, rainfall increased over southern China (22–28°N, 105–120°E), the northeastern China, and the Korean Peninsula (35–45°N, 121–130°E) by 39 mm (~6%) and 33 mm (~7%), respectively.

3.3. Simulated Surface Energy Budget and Circulation Changes

To understand the decreased surface air temperature, we analyzed the mean changes in the surface energy budget for areas with LUCCs in northeastern (40–49°N, 119–126°E), northern (33–42°N, 105–116°E), and southern China (23–32°N, 104–117°E). Model grid cells exhibiting changes in the surface energy budget agreed well with grid cells having LUCCs (Figure 7). In association with conversions from grassland/forest to cropland, the surface albedo increased by 0.03, 0.01, and 0.07 over northeastern China, northern China, and southern China, respectively. Consequently, the net surface solar radiation decreased by 4.5 W m$^{-2}$, 1.4 W m$^{-2}$, and 13.0 W m$^{-2}$, respectively. There were concurrent increases in the surface latent heat flux of 9.6 W m$^{-2}$, 7.3 W m$^{-2}$, and 4.1 W m$^{-2}$ and decreases in the surface sensible heat flux of 12.0 W m$^{-2}$, 6.6 W m$^{-2}$, and 17.2 W m$^{-2}$ over northeastern, northern, and southern China, respectively. In northern and northeastern China, the conversion from grassland to cropland increased the surface albedo and contributed to decreases in the net surface shortwave flux. In addition, the surface latent heat increased, which decreased the surface temperature and reduced the sensible heat flux at the surface. However, in southern China, where cropland replaced forest, the increase in the latent heat was relatively small. In response to this change, the surface air temperature decreased slightly in this region.

To explain the variations in rainfall, wind field and 850 hPa geopotential height changes were analyzed (Figure 8). There was a cyclonic wind anomaly over northeastern China and the Northern Korean Peninsula (30–45°N, 110–140°E), which was accompanied by anomalous northerly winds in northern China and anomalous southwesterly winds along the coast of southern China (20–25°N, 100–120°E). These anomalous winds were indicative of a weakened summer monsoon over eastern China, which contributed to decreased (increased) rainfall over northern China (southern China). A weakened summer monsoon was consistent with the above mentioned temperature changes; the significant negative surface air temperature anomaly over northern continental China decreased the temperature contrast between the eastern Chinese continent and the northwest Pacific Ocean. As a result, the summer monsoon over eastern China was weakened.

The spatial distribution of the geopotential height anomaly at 850 hPa was consistent with the wind field. The spatial distribution was characterized by an anomalous decrease in the geopotential height; the maximum decrease was 10 geopotential meters at the border of northeastern China and the Northern Korean Peninsula (Figure 8). This decrease in the geopotential height had an equivalent barotropic structure with a similar pattern at 500 hPa, which tilted slightly westward and had an enhanced anomaly compared with that at 850 hPa (figure not shown). These negative geopotential height anomalies from 850 to 500 hPa aided in the formation of increased rainfall over northeastern China and the Korean Peninsula. The decrease in the geopotential height may be primarily attributed to the decrease in air temperature over northern and northeastern China. Because this study indicated decreases in both the surface atmosphere...
Figure 6a and lower tropospheric (figure not shown) air temperatures in northern China, the thickness of the corresponding layer in the lower troposphere decreased, which ultimately decreased the geopotential height from the surface to the midtroposphere in this area.

To help explain the occurrence of rainfall anomalies, we analyzed changes in tropospheric moisture transport, which were represented by vertically integrated moisture transport from 925 to 200 hPa (figure not shown). The spatial distribution of the moisture transport anomalies in the troposphere resembled the wind field anomaly at 850 hPa, i.e., a southwesterly (northerly) moisture transport anomaly located over the southeastern coast of China (northern China). The northerly moisture transport anomaly over northern China was not favorable for the northward propagation of the Mei-Yu front, which reduced rainfall over the lower reaches of the Yangtze River valley and increased rainfall over southern China. Meanwhile, the enhanced southwesterly moisture transport anomaly over southern China resulted in increased rainfall in this region.

3.4. Examination of the Relationship

In this study, model simulations indicated that changes in land use/cover may have led to a surface cooling effect over northern China by modifying the surface energy balance. However, besides the LUCCs, cloud cover differences between EXP 1 and EXP 2 may affect the surface air temperature because clouds can influence the surface energy balance through radiation reflection and changes in the surface latent and sensible heat fluxes accompanied by precipitation. It is possible that the surface energy anomaly was primarily caused by changes in cloud cover. To exclude the effect of cloud cover changes, we examined the anomaly in the surface air temperature during summer days with small cloud cover changes in each individual grid cell. Here a day was considered to have small cloud cover changes if the difference in the daily cloud fraction (vertical integral of the column) between the two simulations was less than 0.1 in each grid cell. The selection of this criterion was based on two aspects: (1) the selection of cloudless days needed to be sufficiently strict to exclude cloudy days and (2) the number of cloudless days needed to be sufficiently large to ensure an adequate sample size. The results showed that an extensive cooling signal was detected over northern and northeastern China (figure not shown). These results support the finding that the land cover conversion from grassland to cropland over northern and northeastern China may have resulted in the reduced surface air temperature.

Furthermore, we examined the possible linkages between the surface cooling effect in northern and northeastern China and the cyclonic anomaly covering northeast China and the Korean Peninsula based on the NCEP-DOE Reanalysis II and the ERA-Interim Reanalysis data sets. The cyclonic anomaly played an important role in increasing rainfall over northeastern China and the Korean Peninsula; we hypothesized that the LUCCs over northern China may have produced this anomaly through a cooling effect at the surface. To test if the simulated relationship was model dependent, we initially defined an air temperature
index, i.e., the normalized values of the annual mean decreases in the surface air temperature over 35–45°N
and 105–115°E in summer during the period 1981–2000. Then, we calculated the regression coefficient of the
air temperature index with the wind vectors and geopotential height in summer at 500 hPa. Similarly, to
exclude the effect of cloud covers on the surface air temperature, only data from cloudless days were used. Here
a cloudless day was defined as a day when more than 80% of the grid cells over the study area (i.e., 35–45°N,
105–115°E) had cloud covers below 0.2; this criterion was chosen for the same reasons mentioned above.

As shown in Figure 9a, associated with a decrease in the surface air temperature over 35–45°N and 105–115°E,
an anomalous cyclone system was found at 500 hPa level with one center covering the boundary between
northern and northeastern China (40°N, 115°E) based on the NCEP-DOE Reanalysis II. Figure 9b shows the
regression analysis results using the ERA-Interim Reanalysis data set. A cyclonic anomaly with one center
over the border between northeastern China and the Korean Peninsula (40°N, 120°E) was observed. Although
the results from the two data sets exhibited some differences in both magnitude and scope, the similar
anomalous pattern indicated that the relationship between the surface air temperature and the circulation
did not depend on the data that were used. Moreover, the results derived from observations were also found
to be consistent with the simulated results, which suggested that the surface cooling over northern China
may have enhanced the cyclonic anomaly over northeastern China and the Korean Peninsula.

4. Summary and Discussion

Eastern China has undergone significant anthropogenic LUCCs, including deforestation and agricultural
expansion, over the last three decades. This study investigated the possible climatic response to realistic
LUCCs during recent decades using two 21 year (1980–2000) simulations with land use/cover data
from the 1980s and the 2000s. The Weather Research and Forecasting (WRF) model with the Noah-MP
land surface scheme was applied to investigate the climatic response. The results from this study
demonstrated that in association with agricultural expansion, the surface albedo increased by 0.03, 0.01,
and 0.07, resulting in a decrease in the net solar radiation by 4.5 W m⁻², 1.4 W m⁻², and 13.0 W m⁻² over
northeastern, northern, and southern China, respectively. In northern and northeastern China, where
cropland replaced grassland, the surface latent heat flux increased by 9.6 W m⁻² and 7.3 W m⁻²,
respectively, leaving the surface temperature decreased by 0.5°C and 0.3°C, respectively, along with
reduced sensible heat fluxes. However, in southern China, where cropland replaced forest, the relative
increase in the latent heat fluxes was small; the surface air temperature decreased slightly by 0.1°C. The
extensive cooling effect over northern continental China reduced the temperature gradient between the
Chinese continent and the northwest Pacific Ocean. The summer monsoon over northern China was
subsequently weakened, resulting in a decrease in summer rainfall of approximately 14 mm (~3%) over
the lower reaches of the Yangtze River valley (28–33°N, 100–121°E), while an increase in rainfall of
approximately 39 mm (~6%) was found over southern China (22–28°N, 105–120°E). In addition, the
cooling effect in northern China may have decreased the geopotential height, which could lead to an
anomalous cyclonic circulation from the surface to the midtroposphere over northeastern China and the
Korean Peninsula (35–45°N, 121–130°E) and an increase in rainfall of approximately 33 mm (~7%). In
general, we discovered that local land use conversions in some regions of eastern China may have
affected the surface air temperature and rainfall patterns over eastern China and possibly the Korean
Peninsula through circulation modifications.

A realistic depiction of land surface processes should include a dynamic vegetation model, which may
account for boreal greening caused by air temperature and atmospheric CO₂ concentration changes [Piao
et al., 2006] and vegetation death changes caused by cold and drought stress. The inclusion of a dynamic
vegetation model may result in a different effect on the regional climate. Furthermore, results may differ from
the present findings if urbanization [Bai et al., 2014] and anthropogenic heat release [Flanner, 2009; Feng et al.,
2012] are included in paired experiments. The potential impacts of these factors should be addressed in
future studies.

Appendix A: Rules for Type Conversions for Land Cover

The criteria for the spatial aggregation and the type conversions from the land use categories defined by
Liu et al. [2003b] to the USGS categories are summarized in Table A1.
Table A1. Rules for Type Conversions for Land Cover

<table>
<thead>
<tr>
<th>USGS Land Cover Categories</th>
<th>Land Use Categories Defined by Liu et al.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Code</strong></td>
<td><strong>Name</strong></td>
</tr>
<tr>
<td>1</td>
<td>Urban and built-up land</td>
</tr>
<tr>
<td>2</td>
<td>Dry cropland and pasture</td>
</tr>
<tr>
<td>3</td>
<td>Irrigated cropland and pasture</td>
</tr>
<tr>
<td>7</td>
<td>Grassland</td>
</tr>
<tr>
<td>8</td>
<td>Shrubland</td>
</tr>
<tr>
<td>16</td>
<td>Water body</td>
</tr>
<tr>
<td>17</td>
<td>Herbaceous wetland</td>
</tr>
<tr>
<td>19</td>
<td>Barren or sparsely vegetated</td>
</tr>
<tr>
<td>24</td>
<td>Snow or ice</td>
</tr>
<tr>
<td><strong>One to One</strong>: The Total Area of a Land Use Category (Right Column) Accounted for More Than Half of an Individual WRF Grid Cell</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Savanna</td>
</tr>
<tr>
<td>10</td>
<td>Savanna</td>
</tr>
<tr>
<td><strong>Several to One</strong>: The Vegetation Regionalization Map was Used to Determine the Forest Type and the Single Forest Type That Accounted for More Than Half of an Individual WRF Grid Cell</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Deciduous broadleaf forest</td>
</tr>
<tr>
<td>12</td>
<td>Deciduous needleleaf forest</td>
</tr>
<tr>
<td>13</td>
<td>Evergreen broadleaf forest</td>
</tr>
<tr>
<td>14</td>
<td>Evergreen needleleaf forest</td>
</tr>
<tr>
<td><strong>Mixed Land Cover Type. Excluding the Above Conditions.</strong></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Mixed dry land/irrigated cropland and pasture</td>
</tr>
<tr>
<td>5</td>
<td>Cropland/grassland mosaic</td>
</tr>
<tr>
<td>6</td>
<td>Cropland/woodland mosaic</td>
</tr>
<tr>
<td>9</td>
<td>Mixed shrubland/grassland</td>
</tr>
</tbody>
</table>

**Acknowledgments**

The NCEP/DOE Reanalysis II data set was obtained from the Research Data Archive (RDA), which is maintained by the Computational Information Systems Laboratory (CISL) at the National Center for Atmospheric Research (NCAR). The ERA-Interim Reanalysis was obtained from the data server maintained by the European Centre for Medium-Range Weather Forecasts (ECMWF). This research was jointly financed by the China Global Change Research Program (2010CB950903, 2012CB955401) from the Ministry of Science and Technology of China and the National Nature Science Foundation (41471171 and 41375003).

**References**


