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Land use/cover change and regional climate change in an arid grassland ecosystem of Inner Mongolia, China

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ABSTRACT

Conserving and protecting the arid grassland ecosystem in Inner Mongolia under climate change requires large-scale observation and analysis. The interaction between land use/cover change (LUCC) and the regional climate change in this study area is addressed using macroscopic monitoring with remote sensing observation and analysis. The area's LUCC was examined to demonstrate the structural dynamics of the land surface in the past from 1988 to 2011. The results of LUCC showed that agricultural land, high coverage grassland, and low coverage grassland were the dominant land cover types taking approximately 65.3% in total. Developed land constantly increased from 1.4% to 12.7% during the study period due to rapid urbanization in the area. According to the land surface energy balance equations, the four key variables of the regional climate system, (1) normalized difference vegetation index (NDVI), (2) albedo (α), (3) surface temperature (T_s), and (4) evapotranspiration (ET), were calculated for their spatial-temporal pattern dynamic and also to perform a correlation analysis to explore the structure-function relationship in the land-atmosphere interaction. The results illustrated that vegetation degradation caused an increase in albedo by approximately 5% on average by 2007 as attributed to the cumulative effects of the drought since 2003. ET also declined to around 0.8 cm/day in 2007. The correlation analysis results suggested the human land use such as development and agricultural activities made the surface boundary layer less responsive in the land-atmosphere interaction.

1. Introduction

In a regional climate system, land use/cover change (LUCC) is one of the key driving forces involved in the land-atmosphere dynamic. LUCC is also a major concern for vegetation diversity and sustainability of the biogeochemical recycle and energy flows in the surface boundary layer (Anderson et al., 2011). Previous research used data from natural land use surveys and meteorological observations to understand some basic principles and the relevant theories addressing the interacting mechanisms between land ecosystem and regional climate change (Salati and Vose, 1984; Shukla et al., 1990). In the past two decades, the rapid development of remote sensing technology helped researchers to upgrade the scale from local surveys to macroscopic regional and global monitoring (Boegh et al., 2002; Sterling et al., 2013; Li et al., 2015).

Models used to estimate the hydrological cycle and energy fluxes on the land surface have been broadly investigated and developed (Li et al., 2016, 2013; Song et al., 2016). The heat fluxes transferred from the radiation spectrum signal collected by the satellite sensors are used to calculate the energy balance of the land surface (Bastiaanssen et al., 1998; Li et al., 2013). This is the one of the current mainstream methodologies applied to retrieve heat-hydro spatial patterns using the pixel-based satellite imagery analysis. Therefore, models based on remote sensing data allows

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one to combine ecological and meteorological process with the spectrum analysis which contributes to theoretical development in eco-climatology (Li et al., 2013; Teuling et al., 2010).

Many of the relevant previous studies on the issue of the regional climate using remote sensing acquisition focus on the estimation of evapotranspiration (ET). ET links with many ecosystem processes, including photosynthesis, soil moisture, and latent heat transfer, and plays significant role in energy and water cycles with vegetation traits, meteorological conditions, and soil characteristics (Fischer and Turner, 1978). A 'multi-step' model that combines satellite images and meteorological data, called "Surface Energy Balance Algorithm for Land" (SEBAL), has been well formulated and documented. The SEBAL model has been widely applied and in various ecosystems (Bastiaanssen et al., 1998; Li et al., 2013). Another, similar model, Surface Energy Balance System (SEBS), was also developed to map hydrological pattern at a regional scale (Su, 2002). Both SEBAL and SEBS used a residue approach to calculate ET. More recently, the Mapping Evapotranspiration at high Resolution with Internalized Calibration (METRIC) model improved the algorithm based on SEBAL (Allen et al., 2007). Another model, ETWatch, based on the Penman-Monteith ET formula driven by multi-source remote sensing and meteorological data, established an integrated platform involving the localized residue approach method, regional roughness length measurement, and gap-filling model. This integration expresses the comprehensive effective roughness through the vegetation and topography (Wu et al., 2012), and has been successfully applied and validated in the arid region and the basin regions of China (Moiwo et al., 2011). Applying the same fundamental principles of the land surface radiation and energy balance above, the German Aerospace Center (Deutsches Zentrum für Luft-und Raumfahrt) developed a series of functions for the land-atmosphere process variables including ET as an expansion module, ATCOR, embedded as a workstation in the digital image processing and analysis software ERDAS IMAGINE (Hexagon Geospatial, formerly ERDAS, Inc.) (Neubert and Meinel, 2005; Richter and Schläpfer, 2015; Li et al., 2015). The workstation can be used to map the key variables reflecting the regional heat-hydro spatial patterns. In our study, we used the ATCOR workstation with land surface energy balance model to retrieve ET for the study region.

As the indicator of the regional thermal environment, surface radiation temperature (T_s) is another key part in the land-atmosphere interaction of the regional climate system. Most remote sensing platforms have the spectral band of the thermal infrared sensor which can be transferred to calculate T_s. For the satellite imagery of Landsat Thematic Mapping series employed in our study, band 6 illustrates the heat spatial pattern using the basic thermal radiation formula. This is a direct and simpler way to obtain T_s (Teuling et al., 2010). Apart from T_s and ET indicating the regional climatic factors, in this study, vegetation and surface roughness involving the process of ET and surface aerodynamic resistance were also quantified with the remote sensing data analysis. The normalized difference vegetation index (NDVI) and albedo (α) were selected as the key variables representing the vegetation and surface roughness, respectively. Considering their statistical significance shown previously (Li et al., 2013), they were analyzed in this study.

Influenced by human activities and global climate change, land degradation has been observed worldwide, especially in arid regions, such as the grassland in Northwestern China (Eswaran et al., 2001; Zhang and Hai, 2010). Grassland accounts for 40% of China's total land area; and, concurrent with the rapid socio-economic development in recent decades all over China, has been undergoing particularly severe degradation. The degraded landscape features have confounded the interaction between LUCC and the regional climate (Akiyama and Kawamura, 2007). A series of large-scale ecological conservation and restoration projects have been implemented by the national and local governments (Wu et al., 2015). To support these projects, large-scale monitoring and assessment are essential and urgent to analyze the LUCC and measure its effects on the regional climate.

Our study area, the arid grassland ecosystem in the middle of Inner Mongolia Autonomous Region, is located in the ecotone of natural grassland and urban areas in Northwestern China. This area plays an important role in the region's sustainable development and also provides many ecological services including agricultural and husbandry production, soil conservation, and regional climate adjustment, etc. (Tong et al., 2004; Liu et al., 2016). In the past two decades, with population growth and urbanization, the grassland experienced structural changes relating to desertification and climate change. In this study, applying a remote sensing modeling approach, we address the scientific questions: (1) How does the land use/cover of the study area change from 1989–2011; (2) How are the key variables of the land-atmosphere process, NDVI, α, T_s, and ET changing in the area during 1989–2011; (3) What are the relationships among the key variables regarding the different types of land use/cover. Particularly, through a correlation analysis, we reveal the contribution of different LUCC to the thermal and hydrological spatial patterns in the arid grassland ecosystem by testing the hypothesis that natural land cover has stronger effects on the regional climate than the human land use.

2. Data and methodology

2.1. Study area

The study area, in the middle of Inner Mongolia Autonomous Region in China, cuts across several regions primarily in the southern region of Siziwang Banner and western region of Chahar Banner and includes the cities Ulanqab and Hothot (between 110°20′E–113°E and 40°20′N –42°40′N; Fig. 1). The area is an arid grassland region mainly containing the temperate and desert grassland. The selected area covering one complete scene of a satellite image (shown in the dashed square frame in Fig. 1) covers approximately 30,625 km^2 (175 × 175 km). The region is hilly in the south with a mean altitude of 1014 m, and a decreasing gradient in elevation in the southwest-northeast. A weather station is located in the rural district of the capital city, Hohhot (Table 1).

2.2. Data sources

We used images of the study area acquired by Landsat Thematic Mapper 5 (TM 5) sensor at 30 m × 30 m resolution from the Landsat database of U.S. Geological Survey (landsat.usgs.gov). We selected the cloud-free satellite images in the growing seasons of the study area, June to September, for the years, 1989, 1993, 2000, 2007, and 2011. The meteorological data including relative humidity and air temperature from the local weather station were collected from China Meteorological Data Sharing Service System (cdc.cma.gov.cn).

2.3. Interpretation of the satellite image for LUCC

The supervised maximum likelihood method was applied with the digital image processing software, ERDAS 2011, to make the visual interpretation based on the satellite imagery. The land covers were classified into two categories and nine types (Table 2).

2.4. Modeling for the key variables of the regional climate

We used the value adding products (VAP) of ATCOR2 module in ERDAS IMAGINE 2011 to retrieve the surface energy balance and