Science of the Total Environment 596–597 (2017) 256–265

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Response of evapotranspiration to changes in land use and land cover and climate in China during 2001–2013

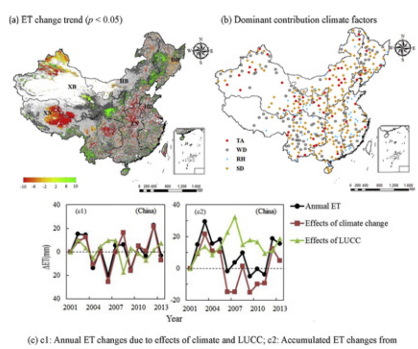
Gen Li [a,b], Fangmin Zhang [a,b,*], Yuanshu Jing [a,b,*], Yibo Liu [a,b], Ge Sun [c]

[a] Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters, Key Laboratory of Meteorological Disaster, Ministry of Education, 210044 Nanjing, China
[b] WMO-NUIST Global Research Institute of Applied Meteorology, Jiangsu Key Laboratory of Agricultural Meteorology, College of Applied Meteorology, Nanjing University of Information Science and Technology, 210044 Nanjing, China
[c] Eastern Forest Environmental Threat Assessment Center, Southern Research Station, U.S. Department of Agriculture Forest Service, Raleigh, 27606, NC, USA

HIGHLIGHTS

- Individual effects of climate change and LUCC on ET in China were quantified.
- Effect of climate change on ET was much more significant than effect of LUCC.
- Deforestation had a greater influence on ET relative to afforestation.
- Sunshine duration was the dominant climatic factor for ET changes in China.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 4 February 2017
Received in revised form 7 April 2017
Accepted 10 April 2017
Available online 21 April 2017

Editor: D. Barcelo

Keywords:
Remote sensing
Evapotranspiration
Land use and land cover change
Climate change

ABSTRACT

Land surface evapotranspiration (ET) is a central component of the Earth's global energy balance and water cycle. Understanding ET is important in quantifying the impacts of human influences on the hydrological cycle and thus helps improving water use efficiency and strengthening water use planning and watershed management. China has experienced tremendous land use and land cover changes (LUCC) as a result of urbanization and ecological restoration under a broad background of climate change. This study used MODIS data products to analyze how LUCC and climate change affected ET in China in the period 2001–2013. We examined the separate contribution to the estimated ET changes by combining LUCC and climate data. Results showed that the average annual ET in China decreased at a rate of −0.6 mm/yr from 2001 to 2013. Areas in which ET decreased significantly were mainly distributed in the northwest China, the central of southwest China, and most regions of south central and east China. The trends of four climatic factors including air temperature, wind speed, sunshine duration, and relative humidity were determined, while the contributions of these four factors to ET were quantified by combining the ET and climate datasets. Among the four climatic factors, sunshine duration and wind speed had the greatest influence on ET. LUCC data from 2001 to 2013 showed that forests, grasslands and croplands in China mutually replaced each other. The reduction of forests had much greater effects on ET than change by other land cover types. Finally, through quantitative separation of the distinct effects of climate change and LUCC on ET, we conclude that climate change was the more significant than LULC change in influencing ET in China during the period 2001–2013. Effective water resource management and vegetation-based ecological restoration efforts in China must consider the effects of climate change on ET and water availability.

* Corresponding authors at: Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters, Key Laboratory of Meteorological Disaster, Ministry of Education, 210044 Nanjing, China.
E-mail addresses: fmin.zhang@nuist.edu.cn (F. Zhang), appmet@nuist.edu.cn (Y. Jing).

http://dx.doi.org/10.1016/j.scitotenv.2017.04.080

1. Introduction

Water is an important resource for maintaining the sustainable development of agriculture and other related socio-economic activity. Over the past few years, water scarcity has become a very serious global problem, and water resource allocation is becoming an important issue as a result of population rise and climate change (Sun et al., 2008). There is an urgent need to fully understand environmental effects on water resources for science-based management and rational allocation of water resources.

Evapotranspiration (ET) is an important component of both the hydrological cycle and surface energy balance. In recent years two factors have had increasing effects on ET: land use and land cover change (LUCC) due to human activity, and climate change (Vörösmarty et al., 2000). We must quantify the distinct effects of LUCC and climate change on ET in order to gain an understanding of regional hydrological cycles and energy balances. This understanding will make us better able to maintain ecosystem functions and services, and to ensure efficient water resources managements (Allen et al., 2011a, 2011b).

The global terrestrial ET data product MOD16 was developed based on land surface characteristics from remote sensing and the Penman–Monteith equation (Monteith, 1965). The MOD16 dataset was evaluated by global flux measurement data, and the estimated accuracy of the data reached 86% (Mu et al., 2011). The dataset has been widely used to study temporal and spatial characteristics of ET on a regional scale own certain advantages (Autovino et al., 2016). In China, some researchers (Jia et al., 2012; Zhang et al., 2016a) found that MOD16 is reasonably practicable and trustworthy on the regional scale although MOD16 in some pixels are overestimated or underestimated.

In the context of climate change, the trend of change in ET and its relationship with climate factors have been widely considered (Roderick and Farquhar, 2004; Tang et al., 2011; Irmak et al., 2012; Croitoru et al., 2013). In one study, Peterson et al. (1995) found that although temperature continuously increased, surface evaporation continuously decreased. Roderick and Farquhar (2002) called this contradiction the *evaporation paradox*. In recent years, many scholars around the world have studied the effects of climate change on the temporal and spatial characteristics of ET (Brutsaert Amp and Parlange, 1998; Golubev et al., 2001; Xu et al., 2006a). For example, some studies concluded that ET has decreased in most countries, and that the decrease might be caused by a reduction in solar radiation and a decrease in wind speed (Gao et al., 2006; Zhang et al., 2007; Zheng et al., 2009). ET increases in some individual areas (Yu et al., 2002; Burn and Hesch, 2007; Dinpashoh et al., 2011) were mainly related to increases in wind speed and decreases in relative humidity.

In addition to climate, ET is highly affected by land cover properties such as leaf area index (Sun et al., 2011a, 2011b). Some researchers believed that LUCC had greater impact on the hydrological cycle than climate change (e.g., Xu et al., 2016) and may cancel or mask the effects of climate change (Hao et al., 2011). LUCC affects ET on the regional scale mainly through vegetation changes (e.g., deforestation and afforestation, or grassland reclamation), agricultural development activities (e.g., farmland reclamation, crop cultivation, and agricultural management), and urbanization (Bronstert et al., 2002). ET change rates differ among land cover types that have different underlying surfaces (Olchev et al., 2008; Douglas et al., 2009; Dias et al., 2015).

In previous studies, several researchers have comprehensively quantified the combined effects of climate change and LUCC on ET in China (Li et al., 2009; Kim et al., 2013; Zhao et al., 2016); however, the individual effects of climate change and LUCC on ET change have not been fully explored. Since 2000, China has seen a large change in land cover as a result of rapid urbanization and implementations of a few large scale ecological restoration projects, including *Grain for Green* program, the *Natural Forest Conservation Program*, and *Three-North Shelterbelt Program* (Feng et al., 2005; Qiu et al., 2011; Xiao et al., 2015; Zhang et al., 2015). These massive LUCCs together with climate change have clearly influenced ET in China. There have debate in China on the causes of large-scale changes in water balances. Currently, it is unclear how LUCC and climate change have respectively contributed to change in water resources in different geographic regions (Feng et al., 2016). Whether the LUCCs had determined ET trends or whether the great effect of LUCCs on ET can be ignored in comparison with the effect of climate change on ET becomes an endless debate. Thus, quantification of the individual effect of climate change and LUCC on changes in ET, and determination of the dominant factor have practical significance for the national-scale ecological campaigns amid a changing climate (Ma et al., 2008; Bao et al., 2012; Hao et al., 2015; Xie et al., 2015).

Therefore, the objectives of this study were to: 1) characterize the spatial and temporal variability of ET in China from 2001 to 2013, 2) quantifying individual contributions of climate change and LUCC. Our guiding hypothesis for this study is that climate change may cancel or aggravate the effects of LUCC on regional ET. Research results may offer important knowledge for land and water managers to take proper watershed actions to mitigate the likely effects of climate on watershed water balances.

2. Materials and methods

2.1. Data

The moderate resolution imaging spectroradiometer (MODIS) is a key sensor aboard both the Terra and Aqua satellites which are part of NASA's (the United States National Aeronautics and Space Administration) Earth Observation System. MODIS data products are well validated and used widely across the world (Friedl et al., 2010; Mu et al., 2011; Hu et al., 2015; Zeng et al., 2015). In this study, we used the yearly 500 m MCD12Q1 land cover data based on the International Geosphere-Biosphere Programme classification (IGBP; Loveland and Belward, 1997) (http://ladsweb.nascom.nasa.gov), and yearly 1 km MOD16A3 ET data from the Numerical Terra dynamic Simulation Group at the University of Montana (http://ntsg.umt.edu). All 1 km ET data were interpolated to 500 m using the nearest neighbor resampling method. We reclassified land cover types into five categories: forests, croplands, grasslands, wetlands, and bare lands. The forests category includes evergreen needleleaf forests, deciduous needleleaf forests, evergreen broadleaf forests, deciduous broadleaf forests, mixed forests, and shrublands.

The meteorological datasets used were acquired from the National Meteorological Information Center of the China Meteorological Administration (http://cdc.cma.gov.cn). The datasets include average temperatures (TA) (°C), sunshine duration (SD) (h), wind speeds (WD) at 10 m height (m/s) and relative humidity (RH) (%). Data from 596 meteorological stations were used in the study period. Stations with lost data or data anomalies were eliminated. Fig. 1 shows the regional distribution of the 596 stations according to a Chinese climatic and geographic regionalization (Jin et al., 2016; Zheng et al., 2013). Spatial distributions of each climatic variable at the 500 m resolution were interpolated from all stations and used to match the spatial distribution of ET using the Kriging method, further for calculating contributions of each climatic variable on the regional scale. Finally, the spatial dataset including land cover, ET, and meteorological data was converted into the albers equal area conical projection at the 500 m resolution.

2.2. Methods

2.2.1. Trend analysis

This study assessed the trends of annual ET for the period 2001–2013 with the following linear equation:

$$y = ax + b, (x = n, n+1, \ldots, N) \tag{1}$$